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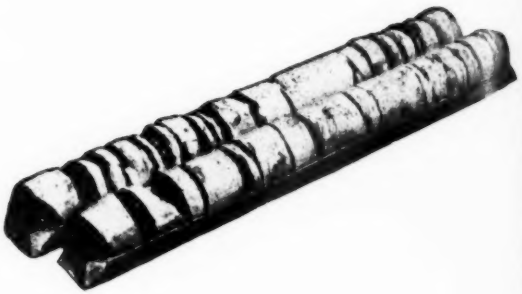

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Volume 17 Number 10

BULLETIN
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AMERICAN ASSOCIATION OF
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OCTOBER 1933

GEOLOGY OF KETTLEMAN HILLS OIL FIELD, CALIFORNIA[1]

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San Francisco, California

ABSTRACT

The Kettleman Hills oil field is one of California's largest oil fields and will be numbered among the major oil-producing areas of the world. It is in Fresno and Kings counties, California, along the western foothills of the San Joaquin Valley, approximately 180 miles southeast of San Francisco.

The Kettleman Hills constitute a topographic feature more than 30 miles in length. Structurally they are composed of two well defined elongate domes, the North and Middle domes, and the northwestern end of what may be a third dome, frequently spoken of as the South dome. The North dome, the largest of the three, may be expected to be productive in an area of 15,000 or 20,000 acres. Oil and gas are produced prolifically from the Temblor formation of Lower Miocene age, which in the North dome is more than 1,500 feet in thickness. The writers discuss briefly the stratigraphy, structure, and mode of occurrence of oil and gas in this field.

INTRODUCTION

At present two great oil fields in the United States are almost constantly in the minds of those interested in the oil industry: the Kettleman Hills field in California, and the East Texas field in Texas. Both are capable of producing such an enormous volume of oil that if either were allowed to produce to full capacity, the complete price structure for petroleum in the United States would be in jeopardy.

The East Texas field is 33 miles long and 5 miles wide. The average thickness of the producing horizon ranges from 30 to 50 feet and it is estimated that its ultimate production will range from $1\frac{1}{2}$ to 2 billion barrels of oil.

[1] Presented before the Association at the San Antonio meeting, March 21, 1931. Revised manuscript received, July 10, 1933.

[2] Standard Oil Company of California.

The areal extent of the Kettleman Hills is much less than that of the East Texas field but the producing horizons are more than 1,500 feet in thickness. Estimates of ultimate productivity from the Kettleman Hills range from 2 to 2½ billion barrels with a volume of gas that runs into astronomical numbers.

It is the purpose of the writers to present a general geologic picture of the Kettleman Hills and the closely related adjacent areas which include a part of the old Coalinga field on the northwest, the Lost Hills field on the southeast, and the western flank of the Diablo Range of the Coast Range Mountains on the west. That part of the Kettleman Hills known as the North dome, which to date constitutes the principal proved productive area in the Kettleman Hills, is treated in somewhat greater detail.

Acknowledgments

The writers wish to take this opportunity to express their thanks and appreciation to W. F. Barbat, Fritz von Estorff, W. S. W. Kew, S. H. Gester, J. O. Nomland, and G. M. Cunningham of the geological staff of the Standard Oil Company of California, for their aid in the collection of data on which this article is formulated. Particular thanks are due to Cunningham for the various data contributed by him and for his helpful suggestions and criticisms. Thanks are also due to H. G. Schenck of the department of geology, Stanford University, Bruce L. Clark of the department of geology, University of California, and G. D. Hanna of the California Academy of Sciences.

History

Prior to the discovery of oil and gas in the Kettleman Hills on November 7, 1928, many wells had been drilled, but most of these were shallow, having reached depths of less than 1,000 feet. The total number of feet drilled prior to discovery was 102,253 or a little more than 19 miles. Not considering the shallow holes drilled under the Mineral Leasing Act of 1920, thirty-seven wells had been commenced and abandoned in Kettleman Hills in the search for oil.

The Milham Exploration Company Well No. 1 (Elliott) was commenced on March 21, 1927, in the southeast corner of Sec. 2, T.22 S., R. 17 E., and was completed, November 7, 1928, with a production of 3,670 barrels of 61° A.P.I. gravity oil and approximately 80 million cubic feet of gas.

The well was drilled to a depth of 7,236 feet, where a string of drill pipe was lost. This was sidetracked and the hole redrilled to 7,108 feet. On October 5, 1928, while drill pipe was being run into the hole

at 5,000 feet, the well blew out and was out of control until November 7, 1928. The oil and gas were first believed to be coming from about 7,200 feet. However, later wells disproved this, and showed the top of the producing zone to be at approximately 6,250 feet.

Location and Topography

The Kettleman Hills, in Fresno and Kings counties, California, is a name given to an isolated range of hills, 30 miles long and 5–6 miles wide, situated 12–15 miles southeast of Coalinga, and the older developed producing Coalinga oil fields.

The highest elevation on Kettleman Hills is about 1,400 feet. The floor of San Joaquin Valley adjacent on the northeast has an elevation of approximately 300 feet, and the Kettleman plain is 400 feet higher.

Kettleman Hills rise abruptly from the alluvium at their northwest end, reach their highest elevation in the area of the North dome, and fade into alluvium at the southeast end of the hills.

An intermittent antecedent stream flows through Avenal Gap in the southeastern part of the hills. Within the main part of the hills, all of the larger drainage is of the consequent type. The topographic axis of the hills is southwest of the structural axis, and in the part of the hills adjacent to the Diablo Range.

Viewed from the air at an elevation of 10,000 feet, the physiographic features and larger structural units of the hills are revealed in spectacular manner. They stand out of the surrounding plains as a long narrow isolated ridge, barren of vegetation, with slightly crescentic shape, the southern tip of the crescent being separated from the main range by Avenal Gap.

The drainage and topography are seen to be typical of the semiarid late Tertiary areas of California. In the central part of the hills the harder sandstones are tending to develop strike ridges with parallel drainage, but the softer outer slopes of the hills are trenched by more numerous sharp transverse gullies.

The central part of the hills has the appearance of rounded sand or sandstone hills and ridges. In marked contrast, the outer fringe of the hills, containing exposures of the Tulare formation, has an intricate lace-like design which terminates abruptly at the alluvium contact.

In the northern part of the hills, the domal structure of the North dome is clearly indicated from the air by the lacy fringe of the Tulare exposures, but very few of the details of structure in the central core are visible.

In the southern part of the hills, in the Middle dome and South

FIG. 1.—Aerial photograph showing northwestern end of North dome of Kettleman Hills, Kings and Fresno counties, California. By courtesy of Fairchild Aerial Surveys, Incorporated.

dome areas, the details of the structure are more easily seen. In addition to the fringe of the Tulare exposures, outcrops of the more prominent beds in the underlying formations swing around the axes of the domes in concentric rings.

STRUCTURE

GENERAL STATEMENT

The Coast Range Mountains bordering the San Joaquin Valley are a complex series of fault blocks set *en échelon*. The Diablo Range, which is the easternmost range bordering the valley, involves a series of sedimentary rocks more than 23,000 feet in thickness, composed of formations which range in age from Jurassic to the most recent alluvium. The Kettleman Hills form a part of a general zone of folding and faulting which extends from the middle part of the Diablo Range into the western margin of the San Joaquin Valley. This general line of folding has been designated as the Coalinga anticline.[3] It is one of the most extensive zones of folding in the Coast Ranges of California and, including the Coalinga East Side anticline on the northwest and the Lost Hills anticline on the southeast, is more than 75 miles in length. It is typical of the structures along the eastern margin of the Coast Ranges bordering the San Joaquin Valley. Such structures ordinarily commence as faults in the higher part of the Coast Ranges. The lines of movement or faulting are not quite parallel with the general trend of the Coast Ranges, but diverge eastward or valleyward at a small angle. Approaching the valley the intensity of the movement, as a rule, becomes less and folding in a large measure replaces the faulting. The faulting in some degree, however, is never entirely absent. The zones do not consist of simple, single, continuous folds, but instead, zones of movement slightly tangential to the major trend of the Coast Ranges along which there are ordinarily several *en échelon* anticlinal folds. That such is the condition is to be expected from the fact that acute diastrophic action has taken place along the whole of the Diablo Range from Mount Diablo on the north to the Tehachapi on the south.

The earth movements had their inception at least as early as Franciscan (Jurassic) time and some of them were active through the Cretaceous and into the late Tertiary. According to Bruce L. Clark:[4]

[3] Ralph Arnold, and Robert Anderson, "Geology and Oil Resources of the Coalinga District, California, *Bull. U. S. Geol. Survey 398* (1910), pp. 165–66.

[4] B. L. Clark, "Tectonics of the Coast Ranges of Middle California," *Bull. Geol. Soc. Amer.*, Vol. 41 (1930), pp. 750–828.

. . . There is no evidence in the Coast Ranges of any basin having been formed as the result of folding; apparently all are fault troughs, either the result of the tilting of the block with the fault on one side only or bounded by faults on all sides. Some of the smaller basins are comparatively simple, the floor being formed of only one block. The larger basins, as a whole, are fairly complex, the floors being traversed by major primary faults which were active during at least part of the periods of deposition. The result of this was a very uneven floor of deposition. Part of the time only a portion of the basin would be submerged and receiving sediments and at other times the whole basin would be undergoing sedimentation.

The concept that the major basins were made up of series of heterogeneous blocks is very important; under these conditions abrupt overlaps took place at the fault lines. Very seldom do we find overlaps that are of the fingering or lenticular type, but the formations thicken and thin suddenly, and almost invariably this takes place at the line of a major fault. This sudden thickening and thinning, as already brought out in the statement of the "Criteria for major faults," is an important aid in the location of the faults themselves.

The Coalinga anticline is a long undulating fold with a general southeasterly trend. It probably has its inception in the vicinity of the New Idria fault near New Idria in Franciscan rocks. The anticline plunges southeast, involving successively Cretaceous and Tertiary formations. In the vicinity of the East Side Coalinga oil field the Upper Cretaceous Moreno shales swing abruptly around the plunging fold. The Cretaceous is similarly followed in turn by the Eocene, Oligocene, Miocene, Pliocene, and Pleistocene formations. Throughout the East Side Coalinga field the Coalinga anticline is acutely asymmetric with dips on the southwest flank as steep as 70° and on the northeast as steep as 25°.

The anticline plunges beneath the recent alluvium of Pleasant Valley, but rises at the northwest end of the North dome of Kettleman Hills. The North dome is apparently *en échelon* to the anticline of the East Side Coalinga oil field. In the Kettleman Hills proper there are two distinct *en échelon* domes, namely, the North and the Middle domes. At the extreme southeast end of the Middle dome the evidence of folding is interrupted at Avenal Gap. Here the fold plunges beneath the Quaternary alluvium, but reappears offset toward the west in the extreme southeastern end of Kettleman Hills. The anticline can be followed readily southeast, exposing progressively older beds, to a point about 4 miles from Avenal Gap, where it is again lost beneath alluvium. The fold reappears 5 miles farther southeast in a distinct dome 10 miles in length, known as the Lost Hills.

In its general orientation and position the Lost Hills fold appears to be the extreme southeast end of the Coalinga anticline. There is,

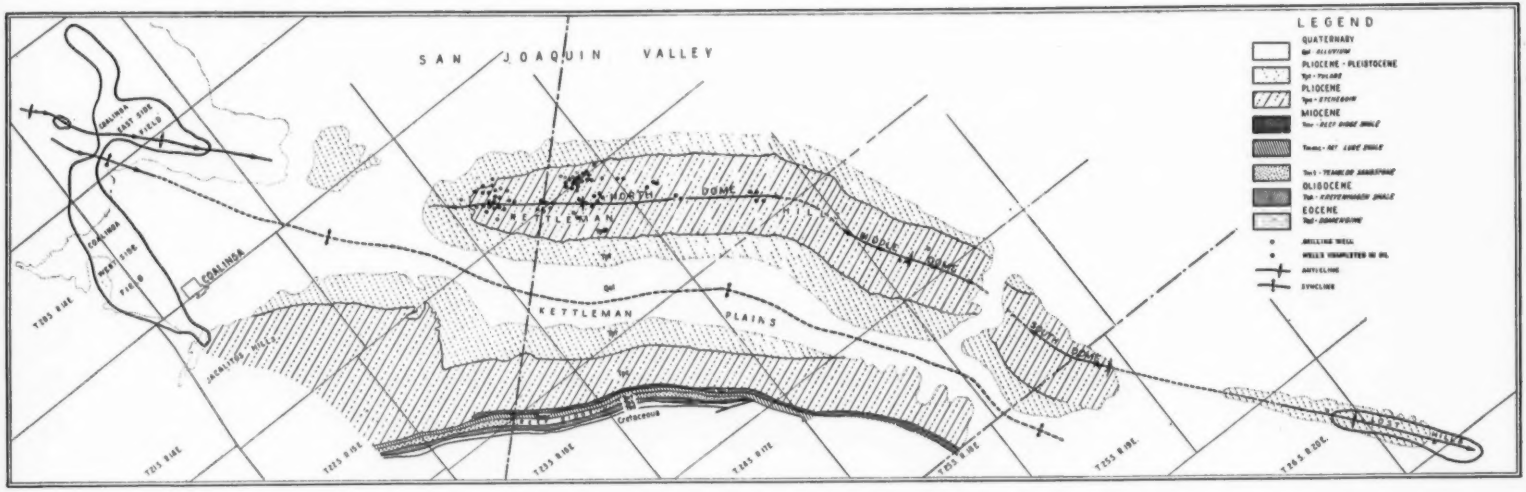

FIG. 2.—Map showing principal formations in Kettleman Hills district, San Joaquin Valley, California.

however, some meager evidence from the cuttings of shallow wells to the effect that the surface beds in the group of hills southeast of Avenal Gap, which form the extreme southeast end of Kettleman Hills, are closed on the southeast and are not a part of the Lost Hills fold. Well correlations in the Miocene formations, however, do not seem to conform with this interpretation and show a continuous plunge from the crest of the Lost Hills fold to the vicinity of Avenal Gap. In the Lost Hills there are missing approximately 6,000 feet of Pliocene strata which are present at the southeast end of the Kettleman Hills. There is some evidence to support the belief that Lost Hills is an older structure than the North and Middle domes of Kettleman Hills and there may be some structural complexity at present not clearly understood in the alluvium-covered area between Lost Hills and Kettleman Hills.

That part of the Coalinga anticline which forms the Kettleman Hills is separated from the Diablo Range on the west by a structural "low" known as the Kettleman plain. The Diablo Range in this vicinity is structurally a complex uplifted block bounded on the southwest by the great San Andreas fault zone. Formations from the Franciscan upward are involved in this uplift. Counterparts of most of the formations which lie beneath the surface of Kettleman Hills are exposed on the northeastern flank of Diablo Range along what is known as Reef Ridge.

Stratigraphy

General character and distribution of formations

The rocks exposed in the Kettleman Hills and along the east flank of the Diablo Range, which are of interest in a study of the Kettleman Hills, include a complex series of sedimentary formations which extend in age from the most recent valley fill to, and including, the Cretaceous.

Due to the fact that diverse earth movements in the Coast Ranges were more or less continuous throughout the whole of this period of geologic time, the formations themselves are to a large degree variable in thickness and lithology. Some formations elsewhere predominating are here very thin or are completely missing. There has been much discussion among geologists as to the age and correlation of some of these formations, and the stratigraphic column and general correlation chart of the San Joaquin Valley (Fig. 3) by no means represents the last word on this subject. Among some of the disputed geologic problems that affect an interpretation of the geology of the Kettleman Hills at present are: the relations of the McLure shale to the Mon-

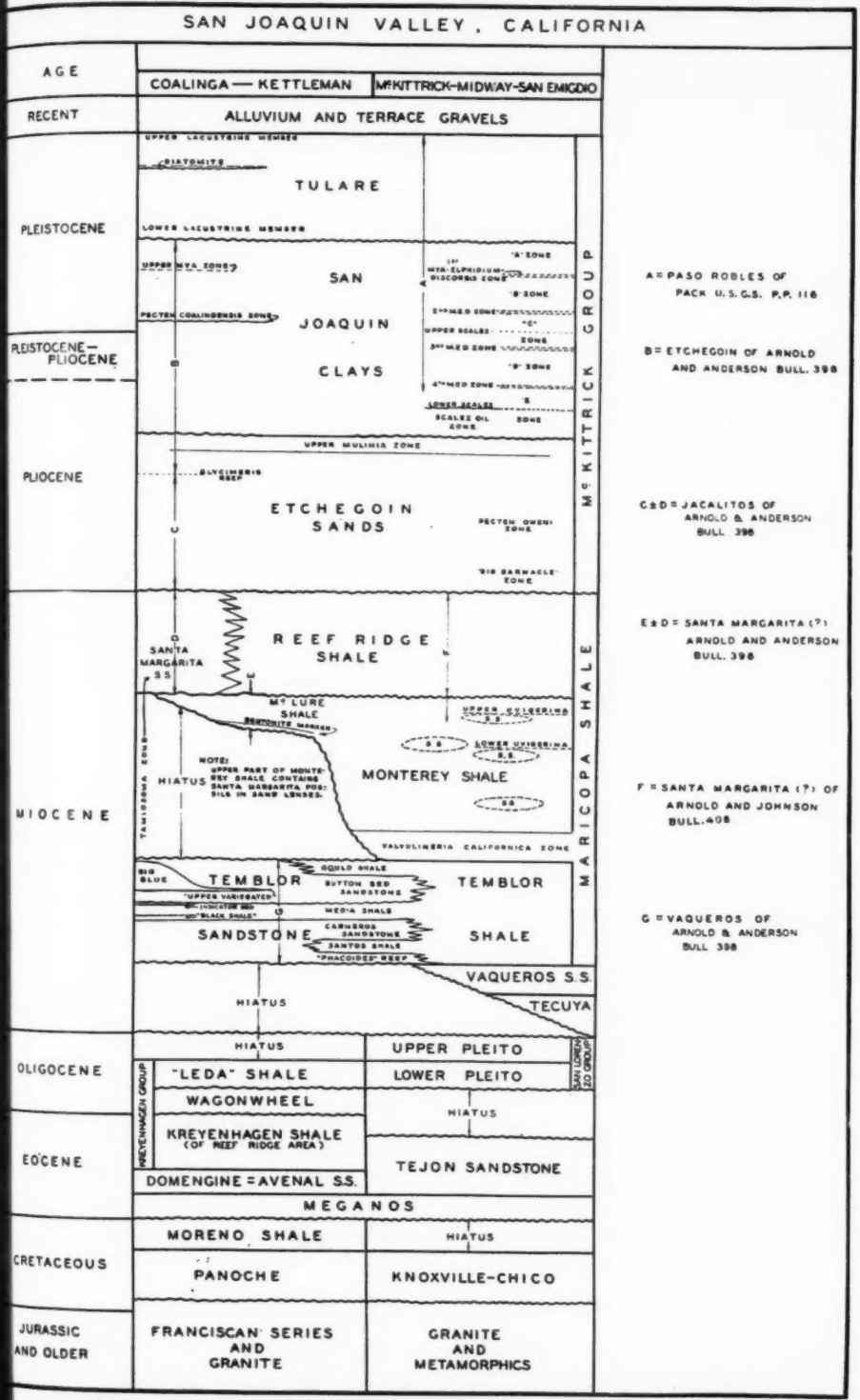

FIG. 3.—Formation correlation chart of west side of San Joaquin Valley, California.

terey and the Maricopa formations; the relations of the Reef Ridge shales to the Santa Margarita; and the correlation of the Oligocene and Eocene formations.

The progressive development of geological knowledge in the San Joaquin Valley has extended through many years. It has been characterized by a gradual growth of slowly acquired knowledge both as to stratigraphy and structure. Moreover, it has been materially advanced in late years by improved and better technique, by more exact detailed methods of work, and particularly by micropaleontology and material obtained from cores of wells.

As a result, the writers have found it desirable to depart from the previous stratigraphic nomenclature in several instances in an attempt to divide the section as nearly as possible at the more prominent stratigraphic breaks. This has made it necessary to redefine the contacts separating several of the formations, but wherever possible, the established formational names have been retained.

Two companion papers, "The San Joaquin Clay of the California Pliocene,"[5] by W. F. Barbat and John Galloway, and "Stratigraphy and Foraminifera of the Reef Ridge Shale, California"[6] by W. F. Barbat and Floyd Johnson, have formed the basis for the stratigraphic nomenclature employed for the beds above the Miocene siliceous shales.

PLEISTOCENE SECTION

TULARE FORMATION

The Tulare formation was named by F. M. Anderson in 1905.[7] The formation as exposed forms a complete belt around the Kettleman Hills and another prominent belt along the lower flank of the Diablo Range. It is composed of fluviatile and lacustrine beds of ill-sorted, little consolidated, rapidly alternating sands, gravels, and clays. The upper members are not fossiliferous, but the lower members contain a plentiful fresh-water fauna. At the northern end of the North dome, the Tulare is about 1,850 feet thick on the west flank of the anticline. On the south end of the North dome on the west flank a thickness of 2,800 feet is estimated, and on the central part of the Middle dome on the same flank a total of 3,300 feet was measured. This increase in measured thickness toward the south is due in part

[5] Manuscript; read before the Pacific Section of the Association at the Los Angeles meeting, November 6, 1930.

[6] Manuscript; read before the Paleontology and Mineralogy Division of the Association at the Houston meeting, March 24, 1933.

[7] F. M. Anderson, "A Stratigraphic Study in the Mount Diablo Range of California," *Proc. California Acad. Sci.*, Geology, Vol. 2, No. 2 (1905).

to a southward thickening and in part to the fact that the recent alluvium apparently laps over a greater part of the upper beds toward the north.

There is reason, based on paleontologic evidence, to believe that the upper part of the San Joaquin clays underlying the Tulare formation is Pleistocene in age. Although Arnold and Anderson[8] were of the opinion that deposition of the Tulare formation commenced during Pliocene time and continued into the Pleistocene, the writers are tentatively assigning the entire Tulare formation to the Pleistocene.

PLIOCENE SECTION

GENERAL STATEMENT

The beds between the base of the Tulare formation and the top of the Miocene siliceous shales have been variously named by previous writers. In 1905, F. M. Anderson gave the name "Etchegoin beds" to the greater part of this series, dividing it into the San Joaquin clays, above, and the Etchegoin sands, below. The entire series was referred to the Pliocene.[9] Arnold and Robert Anderson in the Geological Survey Bulletin describing the Coalinga district issued in 1910, retained the name Etchegoin formation for the beds above a locally prominent *Glycimeris* reef and assigned the rest of the beds above the Miocene siliceous shales to the Jacalitos formation.[10] However, along the southeast end of Reef Ridge, the base of the Jacalitos was placed somewhat higher. The Etchegoin formation comprising much of the San Joaquin clays of F. M. Anderson was referred to the Miocene.

In 1915, J. C. Merriam reported the results of the examination of vertebrate material collected from the Coalinga district.[11] This resulted in placing the Etchegoin and Jacalitos formations of Arnold and Robert Anderson in the Pliocene and suggested the possibility that some of the beds immediately below the base of the Tulare formation might be of Pleistocene age. Nomland's papers dealing with the Pliocene of the Coalinga district did much to clarify the situation.[12] Nomland stated:[13]

[8] Ralph Arnold and Robert Anderson, *op. cit.*, p. 141.

[9] F. M. Anderson, *op. cit.*

[10] Ralph Arnold and Robert Anderson, *op. cit.*

[11] J. C. Merrian, "Tertiary Vertebrate Faunas of the North of Coalinga Region," *Trans. Amer. Philos. Soc.*, Vol. 22, Pt. 3 (1915).

[12] Jorgen O. Nomland, "The Etchegoin Pliocene of Middle California," *Univ. California Pub., Bull. Dept. Geol.*, Vol. 10, No. 14 (April 19, 1917), pp. 191–254.
"Relations of the Invertebrate to the Vertebrate Faunal Zones of the Jacalitos and Etchegoin Formations in the North of Coalinga Region, California," *ibid.*, Vol. 9, No. 6 (January 19, 1916), pp. 77–88.

[13] *Op. cit.*, p. 197.

Thus no break has been found comparable to that assumed by Arnold and Anderson between the Etchegoin and the Jacalitos in the Coalinga region. . . . The term Jacalitos as a formational name must therefore be abandoned and, because of its close relationship to the Etchegoin, it becomes necessary to include the Jacalitos with that formation.

In the earlier paper, Nomland noted the discovery of an unconformity a short but variable distance above the *Glycimeris* zone in Sec. 1, T. 19 S., R. 15 E., probably at the contact at the base of the San Joaquin clays as herein used.[14] Furthermore, Nomland, in the later paper, described the unconformity at the contact at the base of the Pliocene section.[15] In the light of subsequent developments, the unconformities discovered locally by Nomland become extremely significant because they occur at stratigraphic horizons which can be traced in wide areas and, together with the unconformity at the base of the Tulare, are the boundaries of several of the formations as discussed herein.

Following the recent work of Barbat and Galloway,[16] the writers are reverting, in part, to the nomenclature of F. M. Anderson, separating the section between the base of the Tulare formation and the top of the Miocene into the San Joaquin clays, above, and the Etchegoin sands, below. The contact between the San Joaquin clays and the Etchegoin sands is placed at the top of the upper *Mulinia* reef, a prominent marker bed throughout the southern end of the San Joaquin Valley. The local unconformities and the abrupt change in conditions of sedimentation at this horizon are the reasons for its choice as the separation between the two formations. The upper *Mulinia* reef occurs about 500 feet above the stratigraphic position of the *Glycimeris* zone, which is the base of the Etchegoin formation of Arnold and Anderson. The base of the Etchegoin sands is placed at the top of the Santa Margarita (?) of Arnold and Anderson as mapped by them in the southeastern end of Reef Ridge.[17]

SAN JOAQUIN CLAYS

In and around Kettleman Hills, the San Joaquin clays are a mappable unit about 2,600 feet in thickness. There is some evidence of unconformity at the top of the formation below the basal reef of the Tulare formation. The Tulare rests on various beds of the San Joaquin clays, in places coming down onto the shale beds which generally oc-

[14] *Op. cit.*, p. 80.

[15] *Op. cit.*, p. 201.

[16] W. F. Barbat and John Galloway, "The San Joaquin Clay of the California Pliocene," manuscript; Pacific Section of the Association, Los Angeles meeting, November 6, 1930.

[17] *Op. cit.*, p. 92.

cur 25 feet above the Upper *Mya* zone. There is no angular discordance between the basal beds of the San Joaquin clays and the underlying *Mulinia* reef at the top of the Etchegoin sands. However, in the 60 feet of beds at the base of the San Joaquin clays there are found *Mulinia* shells filled with brown sand similar to the matrix of the upper *Mulinia* reef.

The beds included in the San Joaquin clays are fresh- and brackish-water clays and sands. In the upper division the strata are extremely variable both laterally and vertically and in the lower division they grade downward into more massive sandy beds and contain some of the thick-bedded peculiarly blue vivianitic sands which are so characteristic of much of the upper Etchegoin of the Kettleman Hills. The formation as a whole is extremely fossiliferous, with fossil beds ranging from 2 inches to 35 feet in thickness. The more massive vivianitic sandstones extend stratigraphically to about 550 feet above the base. The upper division is, in general, softer and thinner bedded but contains some massive coarse-bedded yellow-to-tan sandstones with thinner strata of graded, white ashy clays, tan-to-red sandstones, yellowish delta clays with a few thin beds of diatomaceous siliceous shale. The uppermost beds are, in part, gypsiferous.

The total thickness of the San Joaquin clays is slightly more than 2,600 feet. The formation apparently thickens toward the south, being approximately 1,850 feet as measured on the northeast flank, and approximately 2,635 feet on the southwest flank of the North dome.

The beds comprising the San Joaquin clays have been referred to the Pliocene by most of the previous writers except Arnold and Anderson.[18] However, the Pleistocene age of the San Joaquin clays above the base of the *Pecten coalingensis* zone suggested by the vertebrate fossils[19] is receiving some measure of confirmation from a study of the climatic zones in the San Joaquin clays.[20]

ETCHEGOIN SANDS

The Etchegoin sands in the area described in this paper consist of a series of marine sands and clays, richly fossiliferous. They are marked at the top by the *Mulinia* reef which lies immediately below the San Joaquin clays. An unconformity separates the base of the Etchegoin sands from the Santa Margarita (?) of Arnold and Anderson[21] as mapped by them at the southeast end of Reef Ridge. At the

[18] Ralph Arnold and Robert Anderson, *op. cit.*

[19] J. C. Merriam, *op. cit.*

[20] W. F. Barbat and John Galloway, *op. cit.*

[21] Ralph Arnold and Robert Anderson, *op. cit.*, p. 92.

northwest end of Reef Ridge the base of the Etchegoin sands is at the top of "Transition zone mapped as Jacalitos formation" by the same authors.[22] The base of the Etchegoin sands occurs at the contact and unconformity noted locally by Nomland[23] and considered by him possibly to mark the top of the Santa Margarita formation.

One of the chief characteristics of the Etchegoin sands of the Kettleman Hills is that they consist largely of peculiarly blue, vivianitic, relatively soft, medium-to-coarse-grained massive sandstone. Close examination reveals minor amounts of brownish and grayish soft sands, grits, and clay beds. Only about 500 feet of the Etchegoin sands are exposed in the Kettleman Hills.

In the Kreyenhagen Hills on the west, the Etchegoin sands, however, attain a thickness of as much as 5,600 feet. Here they are made up of blue sandy clay, bluish-to-brownish clay, massive beds of buff and olive gray sandstone and sandy clay interbedded with pebbly sandstone and gravel and a few strata of fine light-colored clay. In the Kettleman Hills the Etchegoin sands form the crest of both the North and Middle domes and are the lowest of the formations exposed there. They form a prominent, conspicuous belt along the Kreyenhagen Hills on the west and around the flanks of the Coalinga oil field on the north.

In the Coalinga district the Etchegoin sands produce only a minor amount of oil. Farther south, however, in the Lost Hills, McKittrick, and Midway-Sunset districts, they constitute one of the principal oil-bearing formations. In fact, most of the oil of those districts comes from that formation. In the Kettleman Hills several wells have logged oil sands in the Etchegoin but the probabilities are that they will not be commercially productive.

MIOCENE SECTION

REEF RIDGE SHALE

It has been pointed out previously that the basins of deposition in the Coast Ranges were largely faulted troughs, the basins, as a whole, being complex, with uneven floors of deposition. Overlaps and thickening and thinning of formations, therefore, are to be expected. Such conditions exist in and around the Coalinga-Kettleman Hills area, which, combined with the soft and changeable character of the sediments, have confused correlation and made geologic mapping difficult. Recent detailed mapping and data obtained from wells in

[22] Ralph Arnold and Robert Anderson, *op. cit.*, pp. 100–01, Fig. 4 and footnote.

[23] Jorgen O. Nomland, *op. cit.*, p. 201.

the Kettleman Hills have made it necessary to revise and change many of our ideas regarding previously described and mapped geologic units. This is particularly true in regard to the upper Miocene formations.

After penetrating about 4,500 feet of the blue sands and sandy clays of the Etchegoin, wells in the Kettleman Hills encounter caving blue shale and sandy blue shale. Well logs show 600–800 feet of this formation above a thick series of hard brown shales. The blue shale, because of its characteristic development as a brown shale weathering blue along the flanks of Reef Ridge just southwest of Kettleman Hills, has been named the Reef Ridge shale by Barbat and Johnson.[24] They have pointed out that the distinctive character of these strata has been recognized by previous writers. Arnold and Anderson,[25] in their mapping and stratigraphic sections in the southeastern end of Reef Ridge, included the present Reef Ridge shale as an upper member of their Santa Margarita (?) formation. In the northwest end of Reef Ridge, however, the Reef Ridge shale is the "Transition zone mapped as Jacalitos" of the same writers.[26] Later, Nomland recognized the presence of the unconformity previously mentioned at the top of the Reef Ridge shale and suggested that these beds should be included in the Santa Margarita formation.[27] Still later, Henny[28] gave the name McLure shale to "the brown shale of the Coalinga region which was mapped as Santa Margarita (?) by Arnold and Anderson." Because the Reef Ridge shale weathers brown on the outcrops, it is not certain whether Henny intended to include in his McLure shale both the present Reef Ridge and the underlying siliceous shales, or merely the latter. The ambiguity is increased by the fact that Arnold and Anderson were inconsistent in the mapping of the present Reef Ridge shale, sometimes including it as the upper part of the Santa Margarita (?) and sometimes in the "Transition zone mapped as Jacalitos."

Along Reef Ridge, Reef Ridge shales form a zone of blue clay which locally weathers to a brownish cast. It is soft enough to form a topographic depression where it occurs. Due to its lack of hardness, good exposures are rare. It has a thickness in this locality of about 500 feet. Toward the north it becomes more sandy and in the vicinity

[24] W. F. Barbat and H. R. Johnson, *op. cit.*

[25] Ralph Arnold and Robert Anderson, *op. cit.*, p. 92.

[26] Ralph Arnold and Robert Anderson, *op. cit.*, pp. 100–01, Fig. 4 and footnote.

[27] Jorgen O. Nomland, *op. cit.*, p. 201.

[28] Gerard Henny, "McLure Shale of the Coalinga Region, Fresno and Kings Counties, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 4 (April, 1930), pp. 403–10.

of Coalinga it very probably forms a part of the formation mapped there as Santa Margarita. Southeasterly, it increases in thickness, but its surface continuity is lost in the vicinity of Devils Den. South of Devils Den correlative shales form the upper part of the "upper division of the Maricopa formation" as described by Pack,[29] the latter being essentially the same as the Santa Margarita (?) of Arnold and Johnson.[30] Recently the Santa Margarita or Upper Monterey age of the shales underlying the correlative of the Reef Ridge shale in the Temblor Range has been definitely established by the discovery of Santa Margarita fossils associated with the well-preserved skull of a dog, *Borophagus littoralis*[31] in sandstone lenses in these shales near Crocker Springs.[32]

From cores and logs of wells on the North dome, the Reef Ridge shale is found to be composed of spalling blue clay shale which contains a few calcareous streaks. It has a high colloidal content. In some of the wells cores containing worm burrows were found near the base of the formation. In others calcareous shale, which in turn is underlain by a few feet of black shale, forms the basal part.

As a whole it contains a limited fauna of foraminifers, numerous fish scales, diatoms, and plentiful plant carbons. The formation as determined from the wells varies in thickness laterally. It is at least 300 feet thick in the northernmost wells and thickens to at least 600 feet in the southwest flank. It was found to be 650 feet thick in the Ohio Oil Company's Smith well No. 1 in the southern end of the Kettleman Hills and becomes still thicker in the Lost Hills and in the oil district at the south.

MCLURE SHALE

The writers are tentatively using the term McLure shale to designate that body of brown shale recognized in the Kettleman Hills wells as lying below the blue shale of the Reef Ridge and above the Temblor formation. The term is thus restricted to the lower member of the Santa Margarita (?) of Arnold and Anderson in their mapping in the southeast end of Reef Ridge and to the Santa Margarita (?) of the same authors in the northwest end of Reef Ridge. The McLure shale

[29] R. W. Pack, "The Sunset-Midway Oil Field, California, Part I, Geology and Oil Resources," *U. S. Geol. Survey Prof. Paper 116* (1920).

[30] Ralph Arnold and H. R. Johnson, "Preliminary Report on the McKittrick-Sunset Oil Region, Kern and San Luis Obispo Counties, California," *U. S. Geol. Survey Bull. 406* (1910).

[31] V. L. Vander Hoof, W. F. Barbat, and A. Allen Weymouth, *Univ. California Pub., Bull. Dept. Geol. Sci.*, Vol. 21, No. 2, and Vol. 21, No. 3.

[32] Crocker Springs is located on the northeast flank of the Temblor Range, 13 miles northwest of Taft, Kern County, California.

occupies a similar stratigraphic position in the Reef Ridge outcrops to that in the Kettleman Hills well sections, but a part of the lower members apparently are missing along Reef Ridge. It is unquestionably a part of the Maricopa[33] of the Midway-Sunset, McKittrick region on the south. According to G. D. Hanna, it can be definitely correlated as Monterey in age.

At the northwest end of Reef Ridge the McLure shale overlies sandstones containing Santa Margarita fossils[34] and this fact, together with the finding of Santa Margarita fossils in sandstone lenses in shales correlative with the type Monterey in the Midway district,[35] leads to the conclusion that the Santa Margarita formation, as formerly mapped in many areas in California, is only a sandy facies of the upper part of the type Monterey.

The McLure or "brown shale," as it is so frequently called, is essentially a shale formation. The upper members are chocolate-brown in color but weather white. Diatoms are present in abundance. Some yellow calcareous beds are interspersed throughout the shale. Most of them range from 1 foot to 2 feet in thickness. Lower in the section the shale is thinner-bedded and fissile, has a gray-brown appearance when fresh, weathers purple, and contains many thin calcareous beds. A few bentonite beds occur near the base. Some sporbo (oölites) occur near the bentonite. From 40 to 100 feet above the Temblor in the North dome is a thin bed of bentonite which has been found to be an excellent marker used in correlation between wells for the purpose of landing casing above the top of the producing Temblor horizon. In the outcrops along Reef Ridge there is a thin conglomerate at the base of the McLure shale containing pebbles derived from the Franciscan formation.

The writers believe that the McLure "Monterey" is unconformable below the Reef Ridge, and, as explained later, there are evidences of unconformity above the Temblor. In some Kettleman Hills wells considerable thicknesses of carbonaceous sand occur between the Reef Ridge shales and the McLure brown shales at the expense of the brown shale thickness. This sand seems to be more closely related to the Reef Ridge shale than to the McLure shale and may be the result of the filling of erosion channels in the brown shale surface. The Maricopa (shale) of which the McLure shale is unquestionably a part, at-

[33] R. W. Pack, *op. cit.*

[34] Ralph Arnold and Robert Anderson, *op. cit.*, p. 95.
Gerard Henny, *op. cit.*, p. 406.

[35] W. F. Barbat and A. Allen Weymouth, "Stratigraphy of Borophagus Littoralis Locality," *Univ. California Bull. Dept. Geol. Sci.*, Vol. 21, No. 3.

tains a maximum thickness at Carneros Creek on the flanks of the Temblor Range south of Belridge. The brown shale series apparently overlaps as a marine progression toward the northwest, accompanied by the loss of the basal members of the Carneros Creek section, with the result that the *Valvulineria* zone is absent at the Kettleman Hills and along Reef Ridge.

This variation in thickness of the brown shale series developed an interesting problem in determining the amount of closure on the top of the Temblor of the Middle dome, Kettleman Hills. Wells in the North dome, Kettleman Hills, penetrated 1,200–1,600 feet of brown shale. The Petroleum Securities' Burbank well on the Middle dome penetrated 1,926 feet of brown shale; the Ohio well in the north end of the South dome 2,400 feet; and in the Lost Hills, the Universal No. 44, approximately 2,500 feet. Along the Reef Ridge the exposed portion of the McLure shale has a thickness of only about 800 feet. South of Reef Ridge and south of Devils Den along the flanks of the Temblor Range, it rapidly increases in thickness.

In the oil fields of the San Joaquin Valley from Lost Hills south it is classed by most geologists as being the principal source of petroleum of these districts.

TEMBLOR FORMATION

No attempt is made in this article to discuss in detail the Vaqueros-Temblor problem. It is necessary to mention it, however, because of the confusion of names which is to be found in the geologic literature of California. In F. M. Anderson's article, "A Stratigraphic Study of the Mount Diablo Range of California," published in 1905,[36] in discussing the Miocene formation of the Mount Diablo Range he states,

> The underlying Monterey shales at Carneros Springs in the Temblor Range are sandstones and sandy shales which make up an additional thickness of 1500 feet. . . . In the light of stratigraphic studies farther north it is evident that the series of sands and shales below the Monterey shales should be regarded as a distinct member of the Miocene and the name Temblor beds is suggested to embrace this aggregate of strata.

On the other hand, Arnold and Anderson[37] used the term Vaqueros for those lower Miocene formations of the Coalinga region, correlating them with a formation in the region near the coast which was described by Homer Hamlin[38] in 1904. More recent work has shown that

[36] *California Acad. Sci. Proc.*, 3d. ser., Geology, Vol. 2 (1905), p. 169.

[37] Ralph Arnold and Robert Anderson, *op. cit.*, pp. 80–88.

[38] Homer Hamlin, "Water Resources of the Salinas Valley, California," *U. S. Geol. Survey Water Supply Paper 89* (1904), p. 14.

the Temblor of F. M. Anderson is not a time correlative of the Vaqueros and that it occupies a somewhat higher position in the lower Miocene section, being normally underlain by the Vaqueros where both formations are present. In the Carneros Creek section, the top of the Temblor of F. M. Anderson is at the top of what is known as the "Button bed" sandstone. However, the microfauna in the 200 feet or more of beds just above the Button bed is similar to that in shale streaks within the Button bed in well sections, but is dissimilar to that in the overlying *Valvulineria californica* zone.[39] Furthermore, F. M. Anderson includes beds apparently equivalent to this 200-foot shale member in the Temblor of the Kern River area.[40] At Carneros Creek there is no apparent unconformity between the *Valvulineria californica* zone and the 200 feet or more of shale overlying the Button bed. In Kettleman Hills, this 200-foot shale member apparently is largely represented by sand; in some wells, the absence of a sharp contact between the shale and the sand has given rise to the opinion that the unconformity indicated from regional relations could not reasonably be placed at the top of the sand in all of the wells.

Because of its importance as the great oil-bearing formation of the Kettleman Hills and Coalinga district wells, a somewhat more detailed description of the stratigraphy of the Temblor is in order. It will be described (A) from the outcrop section, and (B) from the wells in the Kettleman Hills.

A. *Outcrop section of Temblor.*—The section of the Temblor as it crops out on Reef Ridge along the east flank of the Diablo Mountains consists essentially of well bedded, firm-to-hard fine-grained calcareous sandstone, with lesser amounts of shale and sandy shale. In about the middle part of the section it is characterized by several highly fossiliferous indurated reefs called ledges, between which are softer shale breaks. These form the backbone of what is called Reef Ridge. Contrary to the ordinary conditions found in the softer Tertiary formations in California, many of the individual lithologic members of the Temblor can be traced for long distances along the outcrop. This is particularly noticeable throughout the whole of the Coalinga district and as far south as the southeast part of T. 23 S., R. 17 E. In Big Tar Canyon and Canoas Creek the formation is well exposed and measures about 1,000 feet in thickness. In these localities, it can be divided into three divisions.

[39] G. M. Cunningham and W. F. Barbat, "Discussion, Age of Producing Horizon of Kettleman Hills," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 4 (April, 1932).

[40] F. M. Anderson, "The Miocene Deposits of Kern River, California, and the Temblor Basin," *Proc. California Acad. Sci.*, 4th ser., Vol. 3 (November 9, 1911), pp. 73–148.

1. The top zone ranges from 200 to 250 feet in thickness. It consists of shale, sandy shale, and sandstones, the latter containing the so-called "Button beds" characterized by *Scutella merriami* and *Pecten andersoni*. This zone is directly below the thin conglomerate bed containing Franciscan pebbles at the base of the McLure shale. Some live oil seepages are present.

2. The middle zone comprises about 300 feet made up of prominent hard fossiliferous sandstones and conglomerates which form reefs that stand out in bold relief. Between these reefs are softer, finer sands, shales, and sandy shales. Three such reefs are particularly prominent along Reef Ridge.

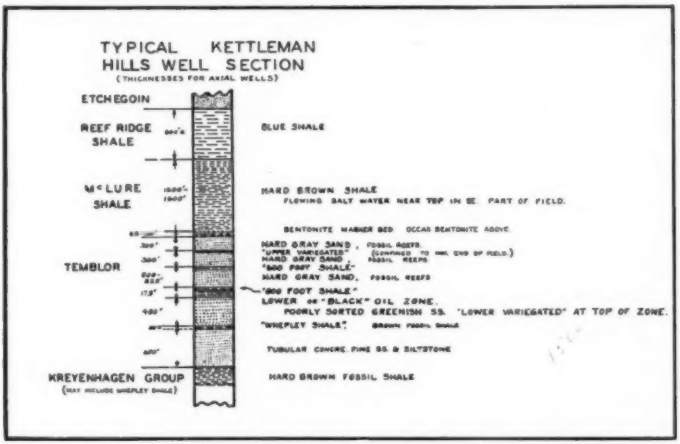
TYPICAL KETTLEMAN HILLS WELL SECTION
(THICKNESSES FOR AXIAL WELLS)
ETCHEGOIN
REEF RIDGE SHALE
BLUE SHALE
McLURE SHALE
HARD BROWN SHALE
FLEMING SALT WATER NEAR TOP IN SE. PART OF FIELD.
BENTONITE MARKER BED OCCAS BENTONITE ABOVE
HARD GRAY SAND, FOSSIL REEFS
"UPPER VARIEGATED" (DEVELOPED TO NW. END OF FIELD.)
HARD GRAY SAND, FOSSIL REEFS
TEMBLOR
"800 FOOT SHALE"
HARD GRAY SAND, FOSSIL REEFS
"800 FOOT SHALE"
LOWER OR "BLACK" OIL ZONE.
POORLY SORTED GREENISH SS. "LOWER VARIEGATED" AT TOP OF ZONE.
"WHEPLEY SHALE" BROWN FOSSIL SHALE
TUBULAR CONCRE. FINE SS. & SILTSTONE
KREYENHAGEN GROUP
(MAY INCLUDE WHEPLEY SHALE)
HARD BROWN FOSSIL SHALE

FIG. 4.

3. Below the reef beds to the Kreyenhagen contact are sandy shales, massive sands, and shaly sands having a thickness of approximately 500 feet. Northward, toward and in the Coalinga area, the Temblor decreases in thickness to less than 600 feet; but southward, along the Temblor Range, and eastward, as evidenced by wells in the Kettleman Hills, it becomes considerably thicker.

B. *Temblor well sections in Kettleman Hills.*—In the North dome of Kettleman Hills, the Temblor section, as indicated by wells, is more than 1,500 feet thick and may be divided into three lithologic units.

1. The upper unit is 800–850 feet in thickness and consists chiefly of sandstones with minor amounts of shale. The upper 50–100 feet of the Temblor consists of fine sands, sandy shales, and shales, possi-

bly correlative in part with the 200 feet or more of shale between the base of the *Valvulineria californica* zone and the top of the Button bed in the Carneros Creek section. The rest of the upper unit is chiefly a sandstone member containing hard fossil reefs. The sandstones are in general hard and uniformly fine-grained. The reef beds are somewhat harder and coarser. In the northwest part of the field, a silty shale streak about 300 feet below the top of the Temblor varies in color from reddish brown to bluish green and purple and is locally designated as the "Upper Variegated shale." The Temblor formation above the Upper Variegated shale carries a little light oil and an enormous quantity of gas under very high pressures.

About 600 feet below the top of the Temblor formation there is a streak of shale about 40 feet in thickness known locally as the "600-Foot shale." The sandstone beds between the Upper Variegated and the 600-Foot shale contain a large volume of oil but with a slightly lower gas-oil ratio than the uppermost zone above the Upper Variegated shale. The lower part of the upper unit, which comprises the sandstone between the 600-Foot shale and the 800-Foot shale, is very similar to the zone above the 600-Foot shale, but it is believed that the oil around the flanks of the field is slightly heavier and darker than the oil of the overlying zones. At present the zone between the Upper Variegated and the 600-Foot shale appears to have the greatest lateral extent of any in the field. On the top of the dome all of the zones of the upper unit contain large quantities of gas and oil of about 60° gravity. Lower on the structure, near the edge of the producing area, the beds below the Upper Variegated shale contain oil which varies from 38° to 34° gravity.

2. The second or middle unit is known as the 800-Foot shale of the black shale. It is approximately 175 feet in thickness and on the top of the dome separates the upper light oil zones from the lower unit which contains dark oil throughout the producing area of the field. This middle unit consists of dark gray-to-black shale with interstratified sandy shale and sand members.

3. The lowest unit is the so-called black oil zone, containing much darker oil on the top of the dome than the higher zones. It has a thickness of 480–500 feet and is made up of sands and minor clay shale strata. The sands are less indurated than in the upper sand division. The shale beds are thin and can not be correlated from well to well. Greenish colors predominate with a few layers of variegated shale giving it a semi-terrestrial appearance. The two wells having the greatest Temblor penetration to date are the Associated Whepley No. 2 and the Standard Oil Company of California No. 41, Sec. 3,

T. 21 S., R. 17 E. The Whepley No. 2, on the north flank, has a penetration of 1,678 feet, and the Standard Oil Company well No. 41, Sec. 3, of 1,481 feet. These wells entered what is called the *Leda* shale, classed by some as lower division Temblor, by others as Oligocene.[41]

OLIGOCENE-EOCENE SECTION

KREYENHAGEN SHALE

Unconformably below the Temblor in the Kettleman Hills and Coalinga district there is found a series of shales and sandy shales which have been termed the Kreyenhagen shales.[42] In *United States Geological Survey Bulletin 398* and *Bulletin 603*[43] this body of shale was tentatively included in the Upper Tejon (Eocene). The Kreyenhagen at its type locality, 20 miles south of Coalinga, has a maximum thickness of about 1,000 feet, and consists essentially of shales with a few limestones, beds of sandstone, and a few lenses of limestones. From the type locality it forms a belt about 15 miles long, disappearing toward the southeast under the overlapping Miocene shales and decreasing in thickness toward the northwest due to an overlap of the Temblor sandstone. North of Coalinga the Kreyenhagen is more fully developed than on the south. Here at the north it is more than 1,500 feet thick and contains upper members not exposed along the Reef Ridge section. As there are reasons to believe that these upper members which contain a considerable thickness of organic shales intervene between the base of the Temblor of the North dome and the top of the Kreyenhagen section as exposed along Reef Ridge, and as this shale may be the source of the Kettleman Hills oil, the stratigraphy of both localities is herewith briefly described.

Reef Ridge section.—Beneath the unconformity at the top of the Kreyenhagen in the Reef Ridge section, there are brown clay shales

[41] Since this was originally written other wells have attained a greater penetration. These wells in the northern end of the North dome did not definitely locate the so-called *Leda* or Whepley shale but below their correlative position additional oil and gas-bearing sands were found. In one well, the North Kettleman Oil & Gas No. 1, on the extreme north in Sec. 24, T. 21 S. R. 16 E., an estimated thickness of more than 1,200 feet of Oligocene was penetrated and the top of the Domengine (Eocene) placed at 10,915 feet. Other oil sands were located below this depth, the well having attained a record depth of 10,944 feet (June 1, 1933).

[42] F. M. Anderson, *Proc. California Acad. Sci.*, 3d ser., Geology, Vol. 2 (1905), p. 163.

[43] Robert Anderson and R. W. Pack, "Geology and Oil Resources of the West Border of the San Joaquin Valley North of Coalinga, California," *U. S. Geol. Survey Bull. 603* (1915), p. 74.

Ralph Arnold and Robert Anderson, "Geology and Oil Resources of the Coalinga District, California," *U. S. Geol. Survey Bull. 398* (1910).

interbedded with opaline shales, approximately 80 feet in thickness. This is followed by softer dark brown-to-black, thin-bedded siliceous, argillaceous, and calcareous shales which on exposure weather white. These are approximately 200 feet thick and are immediately underlain by 200 feet of purplish brown clay shales which contain a rich radiolarian fauna. Below these brown shales are about 80 feet of oil-impregnated platy calcareous shales containing fish scales and *Pecten interradiatus*. The next subdivision, 300 feet thick, contains brittle, yellowish platy calcareous shales interbedded with purple argillaceous shale and some fine-grained gray sandstone. This member also contains lenses of hard gray yellowish weathering limestone. Near the base this is interbedded with gray sandy shale which grades into the bottom member, about 150 feet thick, and is composed for the most part of massive gray sandy shale. The formation as a whole contains comparatively little sandstone, the latter being most commonly found near the base of the formation.

Kreyenhagen north of Coalinga.—Recent work by F. von Estorff[44] on the Kreyenhagen north of Coalinga, indicates that at least two unconformities occur within this group separating it into upper, middle, and lower divisions. It is now considered that the upper part of the Kreyenhagen in the area north of Coalinga is Oligocene, but on the basis of comparative faunas the lower division as exposed on Reef Ridge seems to be more closely related to the Tejon (Eocene). Whether or not this group of shale beds described as Kreyenhagen is Oligocene or Eocene makes little practical difference. Suffice it to say that there exists a body of highly organic shales several hundred feet in thickness unconformably underlying the producing Temblor horizons of the East Side Coalinga field and present in the Kettleman Hills.

The formation north of Coalinga consists of brittle blue-gray-to-purple-to-black radiolarian shale, some thick beds of limestone and a few thick massive beds of soft gray arkose sandstone. The latter occur near the base. The upper part is composed for the most part of hard opal shales. The shales on exposure to weathering are ordinarily white or gray in color but when broken have a decided purple cast. They are very similar in character to the shales of the Monterey group which overlie the Temblor and Vaqueros in other parts of California. Under the microscope some of this shale is seen to be made up largely of the minute skeletons of diatoms with less numbers of foraminifers.

[44] Private report, November 18, 1931.

EOCENE SECTION

DOMENGINE-AVENAL (TEJON) SANDSTONE

Below the lowest member of the Kreyenhagen as classified by the writers, there is found along Reef Ridge a formation composed largely of sands and sandstones of unquestionable Tejon (upper Eocene) age. The sandstones are massive, regularly bedded, and coarse and conglomeratic near the base. Above the coarse basal member the sandstones are somewhat finer, but are indurated to the extent that they form a line of prominent sharp peaks or knobs a few hundred feet back of the reef beds of the Temblor. The basal beds which are 100–125 feet in thickness are succeeded by approximately 550 feet of predominantly sandstone beds which grade upward with apparent conformity into the basal shales of the Kreyenhagen. The formation as a whole contains a rich fauna which is closely identified with the Tejon fauna of the type locality. It also contains a few seepages of oil.

South of Reef Ridge in the vicinity of Devils Den the Domengine or Avenal sandstone, as it is frequently called, becomes much thicker. On the outcrop it is 2,900 feet in thickness and is composed for the most part of relatively thick sandstones.

PRE-TEJON (EOCENE) FORMATIONS

No attempt is made in this article to discuss the rock formations older than the previously described Upper Eocene which may underlie Kettleman Hills. North of Coalinga the Eocene formations, older than the foregoing, are well developed, and beneath the Eocene there are at least two prominent Upper Cretaceous formations of the Chico group, namely, the Moreno shales and the Panoche.

The Moreno shale north of Coalinga is in part organic and produces oil in the old Oil City pool. South of Coalinga the Moreno is missing and Eocene rocks unconformably overlie a great thickness of conglomerates, sandstones, and shales of the Knoxville-Chico group of the Cretaceous.

KETTLEMAN HILLS STRUCTURE

The physiographic unit known as the Kettleman Hills is composed of two elongate, closed domes, the North dome and the Middle dome, and the north end of a third dome. The latter has sometimes been called the South dome, but within the Kettleman Hills it is open toward the southeast and may possibly represent the northwest nose or extension of the Lost Hills structure. As a whole this unit forms one of the major features of the Coalinga anticline previously described.

Compliments of The Texas Company.

FIG. 5.—Kettleman Hills, north end.

The North dome is about 17 miles long and the Middle dome about 7 miles long. The width of both domes between the basal contacts of the flanking Tulare formation is about 3 miles or a little more than 5 miles between the alluvial boundaries. There is little topographic separation between the North and Middle domes; on the other hand, the Middle dome is separated from the north end of the so-called South dome by the broad depression known as Avenal Gap through which drainage from the south half of the Kettleman Plains as well as from McLure Valley is carried to the San Joaquin Valley.

Taken together, the North and Middle domes have a closure of at least 2,700 feet in the Temblor formation. Based on the surface structure contour on the Upper *Mulinia* reef bed at the top of the Etchegoin sands, the North dome is approximately 500 feet higher than the Middle dome. The top of the Temblor on the North dome is a little less than 5,100 feet below sea-level. At the Middle dome it is about 6,900 feet and at Lost Hills about 3,200 feet below sea-level. In other words, the Middle dome is the lowest structurally, being about 1,800 feet lower than the North dome and 3,700 feet lower than Lost Hills. The domes are *en échelon*, but show no evidence of faulting between them.

From surface and well data, the formations as a whole show considerable variation in thickness along the Coalinga anticline. The beds between the Upper *Mulinia* reef and the top of the Temblor formation converge from a thickness of about 8,800 feet in the South dome area to about 5,200 feet in the extreme northwestern part of the North dome. This affects both North and Middle domes by moving the subsurface crests northwest from the surface crests. The effect on the Middle dome is expected to be more pronounced than on the North dome. In regard to the former, subsurface closure figured on the top of the Temblor will amount only to about 300 feet and the subsurface dip on the northeast flank is expected to be about the same as the surface dip, but the dip on the southwest flank will probably be increased considerably above the surface dip. Most of the surface formations and the subsurface formations down to the top of the Temblor show a pronounced thickening in a southerly direction. It is therefore a reasonable assumption that the Temblor of the Kettleman Hills will show a thickening toward the south.

NORTH DOME STRUCTURE

The North dome is an elongate dome having a closure based on top of Temblor datum of about 2,000 feet; that is, figured only to the saddle between the North and Middle domes. The lowest closing con-

tour on the northwest of the North dome is about −7,700 feet and on the south end of the Middle dome it is below −9,000 feet. As the elevation of the Temblor near the top of the North dome is approximately −5,070 feet, the total effective closure for the North dome is approximately 2,700 feet. The top of North dome is comparatively flat but complicated in the surface beds by an elongate down-drop wedge due to faulting possibly contemporaneous with folding. It is not thought that this faulting has had much effect on the Temblor producing horizons.

Based on our interpretation of the structure on the top of the Temblor, the highest parts of the North dome extend from near the center of the NE. ¼ of Sec. 11, T. 22 S., R. 17 E., to near the center of the N. ½ of Sec. 18, T. 22 S., R. 18 E. From Section 11, the northwest plunge is about 5°–6°. Toward the southeast from the center of the N. ½ of Sec. 18, the plunge is very gentle to the southeast corner of Sec. 27, T. 22 S., R. 18 E. From this point to the saddle between the North and Middle domes, the axis plunges about 8°. The fold is slightly asymmetrical and the flanks comparatively steep.

On the northeast flank, surface beds have a maximum dip of 35°. The subsurface dip on the Temblor is estimated at 33°.

On the southwest flank, surface beds farthest away from the axis dip 45° and the subsurface dip on the Temblor is estimated at 65°.

The crest of the North dome and parts of the northeast flank exhibit an elaborate system of faults both transverse and longitudinal in the surface beds.

The transverse faults occur mainly at the ends of the dome and extend farther on the northeast than on the southwest flank. The transverse faults are nearly all normal faults and the average dip of the fault planes is about 65°. The throws of these faults vary from a few feet to about 125 feet.

The longitudinal faults have a maximum throw of 300 feet and are confined to the crest of the dome. On the crest, small block faulting is the rule with the blocks tilted. The blocks are all graben, but with varying displacements. The dip of the fault planes for this type varies from 55° to vertical.

Many of the transverse faults are of the scissors type where they are crossed by a fault of the longitudinal type. In places a fault of one type is found offsetting a fault of another type. In general, it appears that the faulting is due to delayed torsional stresses and settling.

Practically all of the transverse faults, on the northwest end of the dome, have the downthrow on the northwest side. The accumulated throw for these faults is approximately 550 feet. On the south-

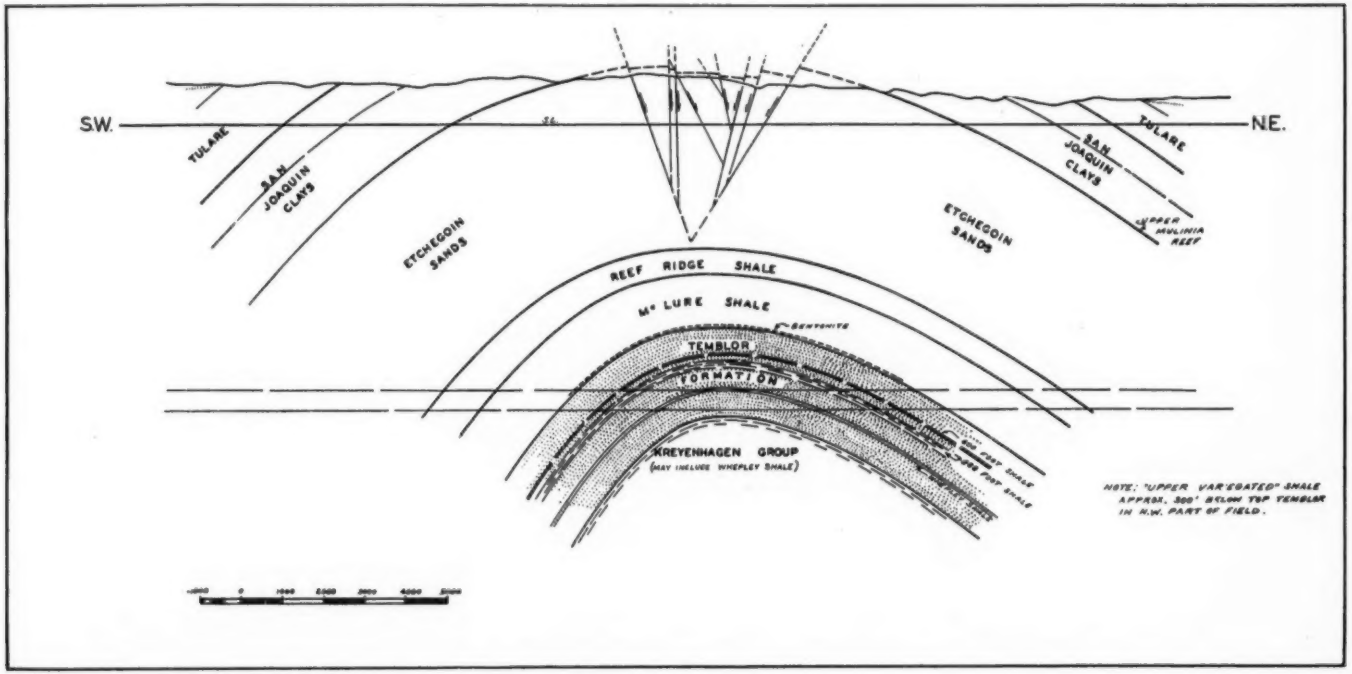

FIG. 6.—Typical cross section, North dome.

east end of the dome the transverse faults have their downthrow on both the southeast and northwest sides, but the net displacement is about 100 feet on the southeast side.

While the productive area of the North dome has not been exactly defined, it appears probable that the area within the so-called red line of the North Dome Kettleman Hills Agreement, as worked out by geologists and petroleum engineers, can reasonably be accepted as proved oil territory. This includes approximately the area surrounded by the −6,700-foot contour referred to the Temblor and involves an area of 13,080 acres. There is some evidence to support the belief that oil and gas in some parts of the North dome will be found below the −6,700-foot contour within the area between the red and blue lines of the North Dome Kettleman Hills Agreement. The blue line in the agreement was intended to bound what might be classed as probable oil land and includes an additional area of 8,120 acres.

MIDDLE DOME STRUCTURE

The Middle dome of the Kettleman Hills came into prominence as the result of a test during December, 1931, made by the Petroleum Securities Company in their Burbank well No. 1, in the SE. $\frac{1}{4}$ of Sec. 30, T. 23 S., R. 19 E. The test, though unsatisfactory due to failure of water shut-off, flowed at the rate of about 2,000 barrels of fluid per day, one-half of which was oil of 51° gravity, and showed as much as 30 million cubic feet of gas. The well was drilled to 9,332 feet but was plugged back to a depth of 9,208 feet. The top of the Temblor was encountered at about 7,559 feet, thus giving the top of that formation a sea-level elevation of −6,984 feet. The well was apparently still in the Temblor at its final depth. It is interesting to note that the bentonite marker which occurs in the North dome at 40–100 feet above the Temblor occurred in the Petroleum Securities well 259 feet above the Temblor.

The Middle dome was proved as a productive field by Standard Oil Company of California well No. 6, Sec. 29, T. 23 S., R. 19 E. This well reached the top of the Temblor sand at a depth of 7,528 feet. It was drilled to 7,885 feet and was plugged back to 7,825 feet, the production being from beds equivalent to the top 300-foot zone of the North dome. The well was completed through $4\frac{3}{4}$-inch tubing, April 25, 1932, producing about 1,400 barrels of 53.8° gravity oil.

The Middle dome is considerably smaller than the North dome, having a length of about 8 miles and a total width between the alluvium Tulare contact of approximately 5 miles. Present data are inadequate to determine with any certainty the extent of the productive

area on the Middle dome. An isochore map covering the area of the North and Middle domes has been constructed and from this a subsurface map with contours on top of the Temblor sand has been compiled. On the basis of this map the top of the Temblor sand on the Middle dome is calculated at a little less than −6,900 feet and the saddle between the North and Middle domes between −7,100 and −7,200 feet.

Erosion has cut somewhat deeper into the crest of the Middle dome than into the North dome and the exposed beds over the entire crest are of a soft friable character. The surface detail mapping here is therefore not nearly so satisfactory as in the area on the north. The surface crest of the Middle dome, based on structure mapping on the *Mulinia* bed of the Etchegoin, is 1,000 feet higher than the saddle at its northwest end, and at least 1,600 feet higher than the saddle at the southeast end. Figured only from the saddle between the North and Middle domes, there is a structural closure on top of the Temblor of approximately 300 feet. On the surface the fold has two small domes and a broad flat top, each subsidiary dome showing a closure of about 100 feet. The two small domes are equally high; one is in the south half of Section 29 and the other in the middle of the south line of the SW. ¼ of Sec. 19, in T. 23 S., R. 19 E. Dips in the surface formations are low along the crest of the fold, but increase to 40° on either side of the axis. Estimated dips on the top of the Temblor on the northeast flank range as high as 45°. The south-west flank is probably steeper than 45°.

The faulting of the Middle dome, though present, is not so conspicuous as on the North dome. It is, however, of the same general type, but the amount of movement of the faults seems to be somewhat less.

Origin and Accumulation of Oil

Source

For many years geologists have held to the theory that the source of petroleum in California was to be found in organic shales which are in many places closely associated with and ordinarily immediately beneath the oil-bearing horizons. This hypothesis is as yet unproved, although it has much supporting evidence in its favor. There has been some tendency, however, blandly to accept the theory as correct and to try to force the facts to fit the theory.

In Lost Hills, Belridge, McKittrick, and the oil fields of the Midway-Sunset district, with the exception of Elk Hills, the oil is closely associated with great thicknesses of highly organic, diatomaceous,

foraminiferal shale of Middle Miocene age.[45] The Elk Hills oil zones are, however, separated from the organic shales by nearly 5,000 feet of inorganic and in part clayey shales. At East Side, Coalinga, along the Coalinga anticline, the Lower Miocene (Temblor) oil is immediately underlain by a thickness of highly organic Kreyenhagen shales. These shales are almost identical in appearance with the Middle Miocene shales on the south and with the so-called Monterey shales of other parts of California, but they are of unquestioned older age. As two wells in the Kettleman Hills have penetrated the Kreyenhagen group beneath the Temblor, it can be stated definitely that organic shales immediately underlie the Temblor, as is the condition in East Side Coalinga field 15 miles northwest and along the Reef Ridge section 6 miles southwest.

The unconformity separating the Temblor from the Kreyenhagen in the adjacent areas where the formations are exposed is definite. Only a part of the Kreyenhagen shales exposed in the section north of Coalinga is found on Reef Ridge, and there is reason to believe that under the Kettleman Hills some of the Upper Kreyenhagen shale members not exposed on Reef Ridge intervene between the base of the Temblor and the top member of the Kreyenhagen of the Reef Ridge section. On the Reef Ridge outcrop and in the East Side Coalinga field the Kreyenhagen shales are not only organic, but in part bituminous. The overlying Temblor sands contain some oil seepages. These sands immediately overlying the Kreyenhagen in the East Side Coalinga field are productive. It therefore seems a reasonable working hypothesis that the Temblor oil in the Kettleman Hills may have had its origin in the Kreyenhagen shales.

There are, however, two other possible sources of oil: (1) from the brown shales that occur in the geologic section above the Temblor, and (2) from shales within the Temblor formation or in shale equivalents of the producing sands.

Porosity of reservoir rocks.—A general discussion of the reservoir rocks in the Temblor of the Kettleman Hills has already been given. It was pointed out that the Temblor was divisible into three units in the entire field with the probability that the upper division could be further re-subdivided into three zones. The producing formation in the North dome has a thickness of more than 1,500 feet. Of this 1,500 feet or more, porosity determinations on a wide range of representative cores indicate that: 65 per cent is sand with a porosity of 14 per cent; 20 per cent is shaly sand with a porosity of about 7 per cent; and 15 per cent is shale with a porosity of 3 per cent and less.

[45] Includes the Maricopa or Monterey and Santa Margarita brown shales.

Oil and gas production and pressures.—This article would not be complete without a word relative to the production of oil and gas and the pressures under which they occur. It was mentioned in the opening paragraphs that the Milham discovery well came in with a production of 3,670 barrels per day of 61° colorless oil with approximately 80 million cubic feet of gas per day. In reality it was an enormous volume of gas spraying a light colorless oil or gasoline of a gravity very similar to that obtained from the extraction plants. Like the discovery wells, several of the earlier wells high on structure were finished in the upper producing zones of the Temblor. All of these have produced light oil with very high gas-oil ratios. Later developments proved that wells finished to produce only from the lowest zone, 480 feet in thickness, had gas-oil ratios of approximately 1,500 cubic feet per barrel and produced oil with gravity varying from 38° to 40° A.P.I.

It has been found, however, that an exceptionally wide range of gas-oil ratios can be obtained depending on: (1) position on structure, (2) zones penetrated and open to production, and (3) method of production and age of well. In fact, the recorded ratios have ranged from 300 cubic feet per barrel to 74,000 cubic feet per barrel. In general it may be said that the gas-oil ratio for the upper or gas cap zones ranges from 40,000 to 50,000 cubic feet per barrel and for the lower or dark oil zone below the gas cap the average is between 2,000 and 2,500 cubic feet per barrel. Similarly, the oil production has varied widely, as the wells have never been allowed to flow for any length of time at full capacity and comparatively little is known of their true potential. Some wells have been estimated as being capable of producing 30,000 barrels or more per day. One well under a restricted production has already produced more than 5 million barrels of oil with a gas-oil ratio of 4,000 cubic feet per barrel. Practically all wells have been produced against high surface back pressures and to date it is impossible to construct decline curves of any value. Shut-in pressures are reported as high as 2,600 pounds per square inch, and comparatively little is known relative to bottom-hole pressures.

Estimates of future recovery from a field of this character producing under restricted conditions for so short a time are subject to various assumptions. Numerous estimates have been made, many of which have approximated 150,000 barrels of oil per acre and enormous volumes of wet gas. A calculation of ultimate recovery of oil, gas, and gasoline for the North dome, based on a porosity method assuming a thickness of 1,500 feet, of which 65 per cent is sand with a porosity of 14 per cent and assuming 25 per cent ultimate recovery,

gives figures in the order of 175,000 barrels per acre and 500 million cubic feet of wet gas per acre. This wet gas in the life of the field is estimated to contain at least 2 gallons of gasoline per 1,000 cubic feet.

CHRONOLOGICAL BIBLIOGRAPHY

1894. W. L. Watts, "Gas and Petroleum Yielding Formations of the Great Valley of California," *California State Min. Bur. Bull. 3* (1894), p. 54.

1905. F. M. Anderson, "A Stratigraphic Study of the Mt. Diablo Range of California," *Proc. California Acad. Sci.*, 3d ser., Vol. 2, No. 2 (1905), p. 181.

1908. Ralph Arnold and Robert Anderson, "Preliminary Report on the Coalinga Oil District, Fresno and Kings Counties, California," *U. S. Geol. Survey Bull. 357* (1908).

1909. Ralph Arnold, "Paleontology of the Coalinga District, Fresno and Kings Counties, California," *U. S. Geol. Survey Bull. 396* (1909), pp. 46–48.

1910. Ralph Arnold and Robert Anderson, "Geology and Oil Resources of the Coalinga District, California," *U. S. Geol. Survey Bull. 398* (1910).

1916. J. O. Nomland, "Relation of the Invertebrate to the Vertebrate Faunal Zones of the Jacalitos and Etchegoin Formations in the North Coalinga Region, California," *Univ. California Pub. Bull. Dept. Geol.*, Vol. 9, No. 6 (1916).

1917. ———, "The Etchegoin Pliocene of Middle California," *Univ. California Pub. Bull. Dept. Geol.*, Vol. 10, No. 14 (1917).

1928. E. H. Musser, "Preliminary Report on the Kettleman Hills Oil Field," *California Div. Mines and Mining Summ. Oper. California Oil Fields*, Vol. 14, No. 5 (November, 1928), pp. 5–17.

1929. E. H. McCollough, "Kettleman Hills Oil Field, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 11 (November, 1929), pp. 1479–83.

1929. G. M. Cunningham, Review of "Preliminary Report on the Kettleman Hills Oil Field," by E. H. Musser, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 11 (November, 1929), p. 1488.

Carl H. Beal and A. H. Heller, "The Kettleman Hills Oil Field," *Oil Bull.* (December, 1929), pp. 1289–95.

E. H. Musser, "Report on the Kettleman Hills Oil Field," *Oil and Gas Jour.*, Vol. 28, No. 30 (1929), pp. 98–99, 102–103.

1930. Stanley C. Herold, "Problem of Drainage at Kettleman Hills," *Oil Weekly* (March 28, 1930), pp. 32–38.

R. I. Brown, "Operations in Kettleman Hills Field," *Oil and Gas Jour.* (April 3, 1930), pp. 39, 139.

Stanley C. Herold, "What Drainage Shows of Kettleman's Future," *Petrol. World* (April, 1930), pp. 65–69, 113–114.

1931. P. P. Goudkoff, "Age of Producing Horizon at Kettleman Hills, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 7 (July, 1931), pp. 839–42.

H. V. Dodd, "Recent Developments in the Kettleman Hills Field," *California State Min. Bur. Summ. Oper.*, Vol. 17, No. 1 (1931), pp. 5–44.

1932. George M. Cunningham, and W. F. Barbat, Discussion: "Age of Producing Horizon at Kettleman Hills, California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 4 (April, 1932), pp. 417–21.

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VOL. 17, NO. 10 (OCTOBER, 1933), PP. 1194-1212, 6 FIGS.

SURFACE FRACTURE SYSTEM OF SOUTH TEXAS[1]

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ABSTRACT

The drainage pattern of the Reynosa Plain area from Guadalupe River to the wind-blown sand area south of Hebbronville, Duval County, shows a peculiar series of straight north-south, northeast-southwest, and northwest-southeast stream courses, which indicate corresponding series of erosion-etched fracture lines. The north-south series is the dominant one. The fracturing affected the sulphur mineralization at the Palangana sulphur mine, produced an impervious zone through the sulphur rock, and a little, but not much, displacement of the cap rock. The dip of the fracture planes has not been determined satisfactorily. The trends of the fractures correspond with deep basement trends which are manifest in the Paleozoic and Pre-Cambrian rocks of the Llano Burnet uplift, the Paleozoic rocks of the Marathon Mountains, the alignment of the salt domes, the elongation of the salt domes, and the Sierra Madre. The immediate cause of the surface fractures of South Texas is the ease with which the weak caliche limestone and the Goliad sandstone fracture. The fundamental cause of the fractures presumably is shearing along old basement fractures, possibly supplemented by gulf-ward tension from the seaward flowage of the sediments and from vertical shear of the coastal subsidence.

INTRODUCTION

The drainage pattern of much of the Reynosa Plain[3] of south Texas delineates a system of north-south, northeast-southwest, and northwest-southeast fractures.

The topography of the Reynosa Plain in general consists of broad, flatly uneven to flatly rolling uplands and broad rolling valleys. Nearly everywhere on the upland, caliche crops out or lies within a few feet of the surface; and in many of the smaller and the shallower valleys, it is buried under only a few feet of alluvium. The regional slope of the area is eastward toward the Gulf of Mexico. The general trend of the course of the major steams across the area varies from southeast to east-southeast.

The physiographic history of the Reynosa Plain is not entirely clear. A plain rises westward from the black waxy Beaumont Plain to a vague caliche cuesta at Palangana in Duval County. There is gradual

[1] Read before the Association at the Houston meeting, March 24, 1933. Manuscript received, July 16, 1933. A study based primarily on the aerial photographic maps of Edgar Tobin Aerial Surveys. Data on the Palangana sulphur mine through the courtesy of the Duval Texas Sulphur Company.

[2] Consulting geologist and geophysicist, Petroleum Building.

[3] Alexander Deussen, "Geology of the Coastal Plain of Texas West of Brazos River," *U. S. Geol. Survey Prof. Paper 126* (1924), p. 8.

transition from the flat, featureless, very youthful plain of the Beaumont clay to the flatly rolling mature caliche upland west of San Diego. West of the vague Palangana cuesta, a slightly lower flatly rolling mature plain rises gently westward to the Bordas escarpment. The Reynosa Plain, therefore, seems to be composite. The plain west of the cuesta through Palangana is erosional. The plain east of the

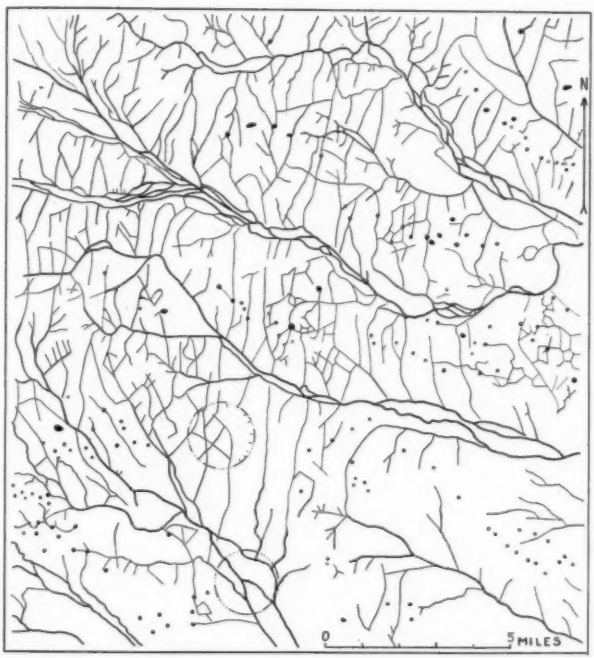


FIG. 1.—Drainage pattern of area in northern Duval County, Texas. (Traced from the aerial photographic maps of Edgar Tobin Aerial Surveys, San Antonio, Texas.) Black dots are faint sink-hole depressions. Dot-and-dash circles give position of Palangana salt dome (northern), and of Piedras Pintas salt dome (southern).

cuesta originally was perhaps either a constructional plain, probably a deltaic plain, or a very perfect peneplain with a veneer of deltaic deposits. But the writer has not yet satisfied himself in regard to its character.

The formations which crop out in the Reynosa Plain are the Lissie, the Goliad (formerly the Reynosa), and the Upper Lagarto. The Lissie extends up the plain which lies east of the Palangana scarp; and the

writer is coming to regard that plain as the Lissie Plain (not necessarily the Lissie Plain of Deussen). The Goliad is the main outcropping formation. The underlying Lagarto is exposed in some of the valleys. Caliche crops out or lies close to the surface in most of the area of the Reynosa Plain.

Caliche is a soil phase characteristic of semi-arid areas; rain water percolating downward through the soil dissolves calcium carbonate from the upper part of the soil and deposits it at greater depth, building up a layer of earthy limestone, calcareous earthy sandstone, and calcareous conglomerate in the subsoil. This explanation of caliche is gaining acceptance among the Texas geologists who come in contact with the caliche of South Texas.[4] Caliche is reported to have been found forming in the Beaumont clay, but its occurrence and development in the Beaumont are not extensive. At the type locality, at Reynosa, Mexico, the Reynosa formation, according to the general conclusion of the geologists who are familiar with the area, is caliche which consists of calcareously cemented gravels on a terrace of the Rio Grande. But the caliche in general is a fossil soil, as it were, and is the product of the past rather than of the present. Its massive development within the caliche area indicates either much more favorable conditions for its formation in the past than at present, or a very long period of time. A fairly complete skeleton of consequent drainage developed early across the Reynosa Plain; but two-thirds of the smaller tributaries seemed not to have developed until the fracture system had been developed sufficiently strongly to influence their own development. The physiography of the Reynosa Plain in several particulars would be more easily understood, if the weak limestones which form most of the caliche were stratigraphic members of the Goliad and not a soil deposit superimposed upon an already mature land surface. There has been rejuvenation since the formation of the Reynosa Plain and the major streams have cut valleys through it.

THREE FRACTURE DRAINAGE TRENDS

A striking tendency toward straight courses and orientation in north-south, northeast-southwest, and northwest-southeast trends is shown by a large proportion of the lesser tributaries, by some of the larger tributaries, and by a few of the main streams.

The tendency toward the north-south course of the tributaries is the most common and striking, and dominates the stream pattern excepting for the main streams. Many lines can be traced for several

[4] W. Armstrong Price, "Origin of Caliche and Reynosa Problem of South Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 5 (May, 1933), pp. 488–522.

FIG. 2.—Aerial photograph of fracture drainage lines, northern Duval County, Texas. (Courtesy of Edgar Tobin Aerial Surveys.) The spots and circular areas are faint sinkholes. The diagonal NW.-SE. straight line is a highway. The fainter straight lines are fences and in the NW. corner a pipeline. The light, spidery lines are automobile and cattle trails, The light, straight-sided patches in the NE. corner and central southern areas are plowed fields.

miles, a few lines as far as 10 miles, and two or three lines for 20 miles, across different stream systems by a concatenation of the tributaries of the successive streams. Opposite tributaries of a stream delineate a straight north-south line which may be at any angle to the main stream. Adjacent tributaries on opposite sides of a divide have a straight north-south valley continuous across the divide.

The northeast-southwest and northwest-southeast trends are less conspicuous and less well developed, but are present. Many small tributaries follow the northeast-southwest trend; and many slightly larger tributaries bend sharply into that trend, follow it for a few thousand feet, and bend sharply out of it into one of the other two trends. Continuous northeast-southwest lines of aligned tributaries commonly can not be followed for more than a mile or two. The major streams and many of the larger small streams have a southeast-to-east-southeast trend which is comparable with the north-south and northeast-southwest trends. It is not as common as that latter trend, but where they are present, the individual northwest-southeast lines commonly can be traced on the map for a longer distance, 1–3 miles, than the northeast-southwest lines.

ASPECT OF FRACTURES

On the aerial photographic maps, these fracture drainage lines are conspicuous by their straightness or flat sinuosity, by their independence of the stream valleys, ridges or uplands which they cross, and by the lack of the wriggling meandering or the short period zigzagging back and forth of the normal small stream. The valleys commonly, but not necessarily, are somewhat sharp and tend to maintain a constant width and not to narrow upstream as much as the normal tributary valley. Many of them have a characteristic individuality, different from the normal streams and stream valleys of the area.

On the ground, one of these fracture valleys crossing an upland commonly is a shallow, possibly indistinct swale or shallow valley, 100–300 feet wide. Where it approaches or opens into a main stream valley, it is a small or medium-sized valley. The swale is marked by a line of ranker mesquite and by a more luxuriant growth of grass and herbs than on the barren upland on either side. The vegetation remains greener longer into the dry periods than does the vegetation on the upland. The greener foliage along these drainage lines is one reason why they stand out so conspicuously on the aerial photographic maps. The line of rank mesquite which marks the course of the western main fracture line across the north rim of the Palangana dome forms a strip approximately 100 feet wide, which looks as if it had

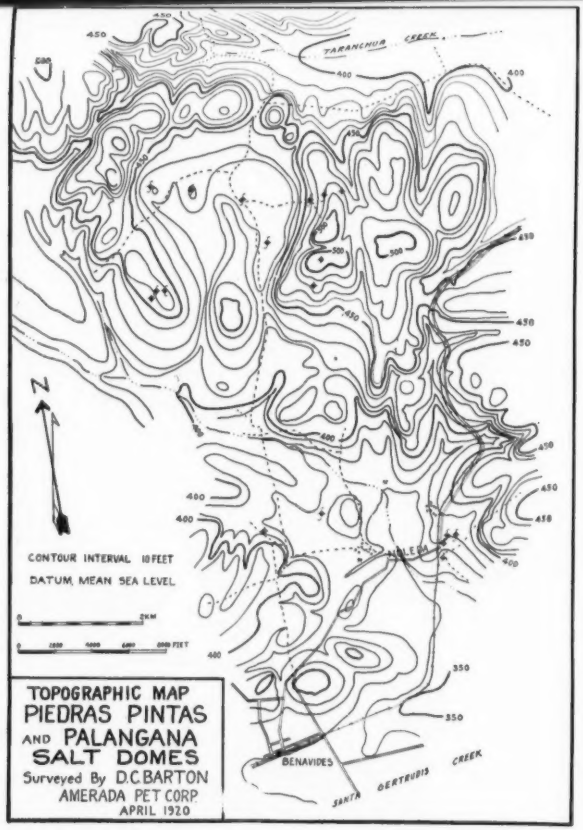
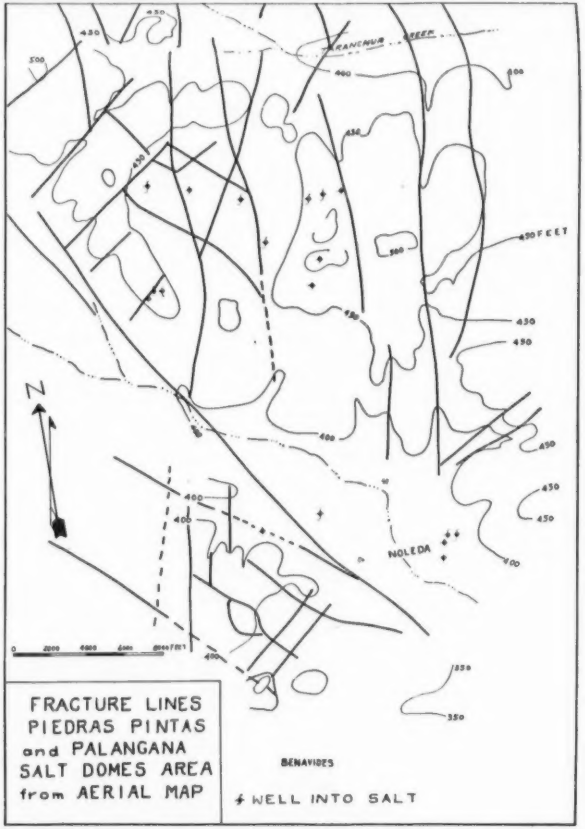


FIG. 3.—A. Topographic map of Palangana-Piedras Pintas area.



B. Fracture drainage lines of same area (traced from aerial photographic map of Edgar Tobin Aerial Surveys).

been laid out with a transit. The soil on the upland is thin; and in general, the caliche crops out or lies at shallow depth. The soil of the swales and valleys along the fracture lines is a deep commonly black clayey alluvium.

These valleys and swales are more numerous and better developed than are the comparable lesser tributaries on the Reynosa Plain east of Guadalupe River.

The topographic expression of these fracture drainage lines is shown by the topographic map of the Piedras Pintas and Palangana salt domes, Duval County (Fig. 3A). The trace of the lines was copied from the aerial photographic map of the area without reference to the topographic map and then was superimposed upon it. The map is based on a few traverses with lateral side-shots; consequently, the contours and the courses of the streams and of the valleys are somewhat generalized. Much of the lack of close fit between the fractures and the corresponding valleys is the effect of the inaccuracy of the topographic map.

Many of the fractures can be seen from their trace on the aerial map to cross the relatively flat lowland areas, although their relief in the lowland areas is not sufficient to be caught by the 5-foot contours of the original map. On the nearly flat level western half of the floor of the Palangana[5] depression, one of the main north-south fractures of the area crosses the western half of the dome. There is a deep notch where the fracture crosses the southern rim and a sharp little notch where it crosses the northern rim. But on the ground within the basin, the presence and the position of the fracture line across the floor of the basin would not be recognized unless they were known. The fracture drainage line stands out most distinctly on the aerial photographic maps; and actually across the floor of the depression, it is a broad, very shallow swale in which the vegetation is a little greener and a little more luxuriant than the vegetation away from the fracture.

SUBSURFACE RELATIONS AT PALANGANA SULPHUR MINE

The subsurface relations of the fractures are partly revealed by the drilling at the Palangana sulphur mine of the Duval Texas Sulphur Company. The "main" sulphur area is approximately 200 acres of the outer part of the southwest quadrant of the top of the dome. A less important, smaller area, the "north" sulphur area, lies near the outer edge of the northwest quadrant of the top of the dome. The

[5] The Palangana dome lies under the topographic basin in the northwestern quadrant of the map; the Piedras Pintas dome lies under the flat lowlands at Noleda.

main sulphur area is crossed by the main north-south fracture line through the western part of the dome (*CD*), by a local northeast-southwest line (*EF*), and by a local, slightly curving northwest-southeast line (*GH*), as shown in Figure 5.

In the cap rock, the main north-south fracture line seems to be represented by an impervious, barren zone in the sulphur rock and by a faint depression in the top of the gypsum of the cap rock. In the Frasch method of mining sulphur, super-heated water is pumped

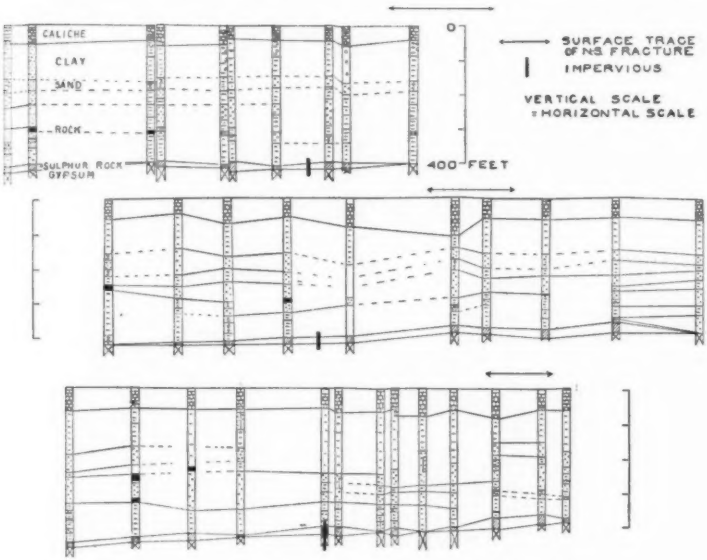


FIG. 4.—West-east structure sections through "main" sulphur area, Palangana.

down wells and out through the surrounding sulphur-bearing rock and then is bled off through bleed wells. In the mining operations in the "main" area, it was found impossible to force the mine water across a slightly curving north-south zone (*A*—*B*) which lies nearly parallel with and just west of the surface trace of the main north-south fracture (Fig. 5). For 1,500 feet, the center of the impervious zone lies 300–400 feet west of the center of the surface trace of that fracture, but near the point of the Duval Texas Sulphur Company's surveys ("O", Fig 5B), it bends eastward and then southward under the surface trace of the fracture. A broader zone grading from barren to very

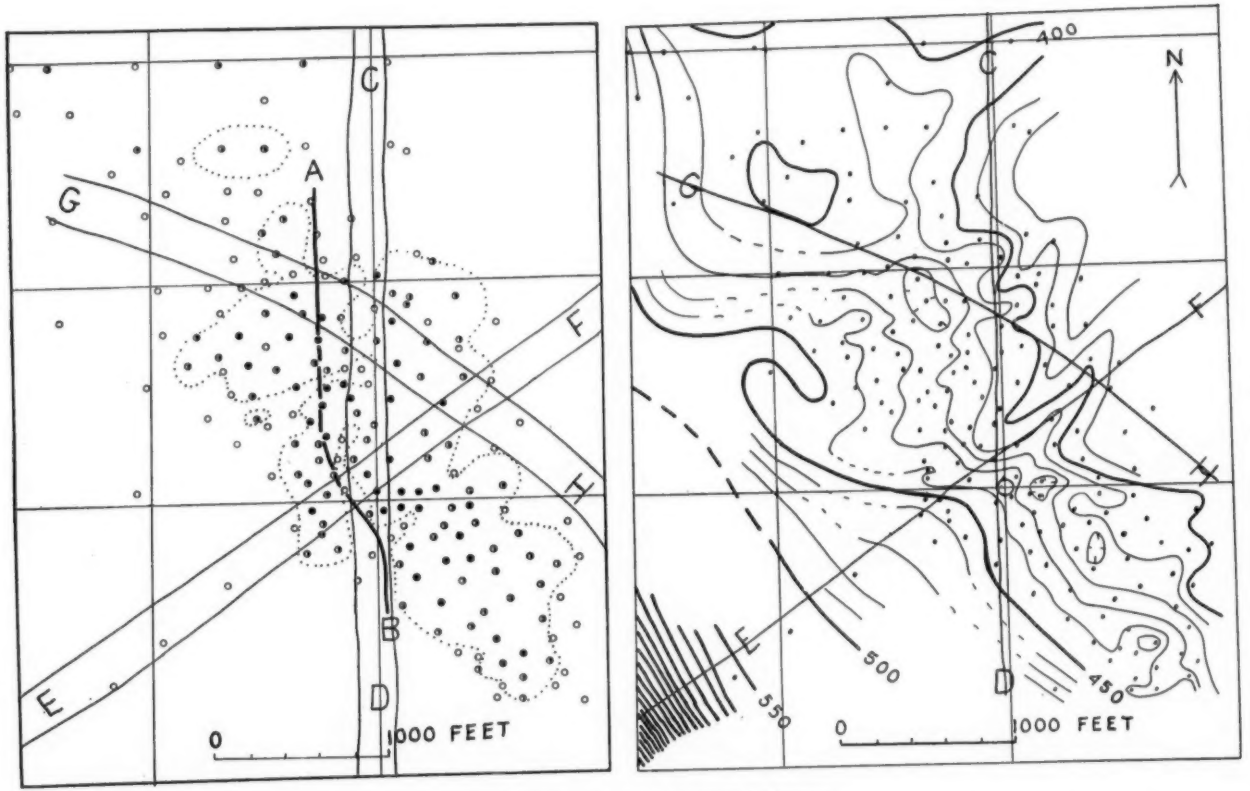


FIG. 5.—Maps of "main" sulphur area, Palangana.

A. Sulphur mineralization: fractures, and impervious zone in sulphur rock. Open circles: barren and non-commercial sulphur wells. Solid circles: richer commercial sulphur wells. Half solid circles: poorer commercial sulphur wells.

B. Structure contours on top of gypsum, and fractures. Solid dots are sulphur wells or sulphur prospect wells.

poor sulphur mineralization in the sulphur rock lies midway between that impervious zone and the center of the surface trace of that fracture; but in the southern part of the area, the zone grading from poor to barren sulphur mineralization does not bend eastward in correspondence with the impervious zone and south of the Duval Texas Sulphur Company's zero east-west line; it lies west of the impervious zone. A shallow indistinct north-south depression in the top of the gypsum lies 100–200 feet west of the impervious zone in the northern half of the "main" sulphur area (Fig. 5B).

In the super-cap sediments, the fracture has produced no effects which are conspicuous in the well-to-well correlation sections of Figure 4. There is a suggestion in those sections, however, of a 5–10-foot depression in a broad zone along the line which connects the impervious zone in the sulphur formation with the center of the surface trace of the fracture. That 5–10-foot depression in the sediments corresponds in character with the broad shallow depression in the surface of the gypsum. The thickness of the caliche tends to be slightly greater under the surface trace of the fracture. A zone of less than normal thickness of the caliche lies fairly closely over the position of the impervious zone in the sulphur rock and bends correspondingly with that zone.

The northeast-southwest fracture line (*EF*) seems to be sharply reflected in the surface of the gypsum. A sharp little northeast-southwest structural ravine in the top of the gypsum lies 50–100 feet southeast of the center of the surface trace of the fracture line; and a corresponding sharp and narrow ridge-like northeast-southwest nose on the top of the gypsum lies 200 feet northwest of the surface trace of the fracture line. There is no associated impervious zone and barren zone in the sulphur rock.

No effects of the slightly curving northwest-southeast fracture line (*GH*) could be recognized in the structure contours on the cap rock or in the map of sulphur mineralization.

The surface trace of these fracture lines across the main sulphur area are shallow swales approximately 200 feet wide. They serve as wet-weather drainage ways; the vegetation is slightly greener and more luxuriant than that in the inter-fracture areas; and the growth of the mesquite is ranker. But the individuality and special character of the fracture lines are much more evident from the aerial maps than they are on the ground.

Vertical displacement of more than 10 feet can not have taken place along the north-south line. Slightly greater displacement with drag on the top of the gypsum can have taken place along the northeast-southwest line and seems the best explanation of the paired structural ridge and ravine on the top of the gypsum.

A. Sulphur mineralization: fractures, special sulphur wells. Solid circles; rock. Open circles: barren and non-commercial sulphur wells. Solid circles; richer commercial sulphur wells. Half solid circles: poorer commercial

A westerly dip of 40°–60° seems to be indicated for the north-south fracture in the northern two-thirds of the "main" sulphur area, and a steeper dip, becoming vertical, in the southern part of the "main" sulphur area. Or, at least the impervious and the barren zones in the sulphur rock and the faint depression in the top of the gypsum seem to be associated with the surface fracture line and to be its effects in the cap rock. It is not clear whether the fracture plane is to be correlated with the barren zone, the impervious zone, or the depression on the surface of the gypsum. Those three features, the surface swale, and the zone of lesser thickness of caliche seem to be associated phenomena, but the writer has not been able clearly to see their relations. But it seems probable that either the impervious zone or the depression in the surface of the gypsum marks the trace of the fracture in the top of the cap rock. The dip of the fracture plane then would be southwesterly in the northern part of the main sulphur area, and would become steep-to-vertical in the southern part of the main sulphur area.

The dip of the northeast-southwest fracture seems to be nearly vertical. The structural ravine and ridge on the surface of the gypsum seem to mark the trace of the fracture in the upper part of the cap rock, and the most probable correlation of the surface trace of the fracture seems to be with the half-way line between the ravine and ridge. The dip of the fracture, therefore, would be approximately vertical.

AGE OF FRACTURES

The age of the fractures must be both pre- and post-sulphur mineralization and post-Pliocene. As the fractures affect the caliche which is a fossil soil on Pliocene beds, they must be post-Pliocene or possibly late Pliocene. The impervious zone must have been developed, at least partly, before the sulphur mineralization and must have reduced, or in places precluded, movement of the sulphur-bearing solutions through what is now the barren zone. The impervious zone presumably was produced by downward infiltration of clay into the zone of what is now the sulphur rock. The sulphur mineralization, in part, is younger than the overlying clays, which presumably are Lower Lagarto, for there has been some growth of sulphur in well-formed crystals within the clays above the sulphur-bearing lime rock of the cap. But there is no evidence that main sulphur mineralization of the lime rock of the cap was not older. The northeast-southwest fracture is not accompanied by an impervious and barren zone. The fracture, therefore, may be later than the sulphur mineralization or it

may have been tight; and downward infiltration of clay into the sulphur rock along the fracture may not have taken place. As the fractures affect the surface on which the caliche is a late Pliocene or early Pleistocene soil, the fracturing, in part, must be post-Pliocene.

DIP OF FRACTURE PLANES

An easterly dip of the north-south fractures and a southeasterly dip of the northeast-southwest fractures are poorly suggested. An attempt to determine the dip of the fractures was made by studying the trace of fractures where they intersect the deeper valleys. The relief of the deeper valleys of northern Duval County ranges from 50 to 100 feet. If a fracture dipped 45°, the shift of the trace of the fracture up or down the valley might be barely perceptible on the aerial photographic maps whose scale is 1 inch = 2,000 feet. The results of the study are given in Table I.

TABLE I

DIP OF SURFACE

Trace of Fracture Lines	
North-South Series	*Number of Observations*
A. Trace of fracture seemingly convex eastward downstream, convex westward over a ridge; that is, seeming to dip eastward	33
B. No deviation of trace up or downstream or up or down a divide; that is, seeming to be vertical	8
C. Trace of fracture seemingly concave eastward downstream and concave westward over a ridge; that is, seeming to dip westward	15
Northeast-Southwest Series	
A. Seeming to dip southeastward	20
B. Seeming to dip vertically	8
C. Seeming to dip northwestward	10
Northwest-Southeast Series	
A. Seeming to dip northeastward	2
B. Seeming to dip vertically	0
C. Seeming to dip southwestward	0

The suggestion of an easterly dip of the north-south series and a southeasterly dip of the northeast-southwest series is not conclusive. Tributary valleys are more likely to enter the main valley at a slight angle downstream than upstream. The downstream direction of the larger valleys has an easterly component. The suggested respective east and southeast dips of the north-south and northeast-southwest fractures, therefore, may be apparent rather than real. The western of the two main north-south fractures across the Palangana dome is convex eastward across the south rim, although the valley across the south rim is cut down to the level of the floor of the Palangana basin. An easterly dip, therefore, is suggested for the area of the northern rim,

and possibly a westerly dip for the area of the southern rim. The "main" sulphur area lies nearer the southern rim than the northern rim. And in that area, the drilling data seem to indicate a westerly dip of 45°. The data are conclusive that the dip of the north-south and of the northeast-southwest fractures is steep or fairly steep. They are inconclusive in regard to the direction of dip.

CORRESPONDENCE WITH FUNDAMENTAL STRUCTURAL TRENDS

These three major fracture systems of South Texas reflect the three fundamental structural trends of the southeastern half of Texas and of northeastern Mexico (Fig. 6).

A northwest-southeast trend of N. 30°–45° W. is the predominant trend of northeastern Mexico and traces of it can be seen in the salt domes of southeast Texas and possibly farther east in Louisiana. The general trend of the front fault of the Sierra Madre, and of the range itself is N. 30°–35° W. The major structures, L de Vallecillo, Laja, and Cerralvo anticlines, of northeastern Mexico in front of the Sierra Madre, the long Chittim anticline in Maverick County, and its continuation in Mexico (not shown in Figure 6) have the same trend. The pre-Cambrian folding in the Llano-Burnet area has a northwest-southeast trend. An alignment of the Gulf Coast salt domes along northwest-southeast fractures was postulated by G. D. Harris a quarter of a century ago. Since that time, aligning the domes has been an (inconclusive) indoor sport of salt-dome geologists. It is easy to get a varied assortment of alignments of four of more domes on the same straight line. But there has seemed to be a foundation for a surmise of an actual northwest-southeast alignment. The newly discovered Clay Creek (30° 15′ N. Lat., 96° 25′ W. Long.), Raccoon Bend, San Felipe, Orchard, West Columbia, Allen, Clements (28° 55′ N. Lat., 95° 30′ W. Long.), together with Damon Mound, give somewhat better evidence for alignment N. 30° W.–S. 30° E. than that available to Harris. Better evidence for the existence of the trend is the slight but definite elongation of some of the domes such as Hockley, Conroe, Humble, Damon Mound, Barbers Hill, and Batson along the axes with a strike slightly north of northwest. Farther east in Louisiana, the Five Islands line has a northwest-southeast strike and is one of the two clearly defined alignments of the Gulf Coast salt domes. The trend of the Preston anticline-Leonard Celeste nose in northern Texas and southern Oklahoma (33°–35° N. Lat., 96°–97° W. Long.) likewise is N. 25°–45° W.

The northeast series of fractures of south Texas has a strike of N. 30°–45° E. A trend of N. 35°–50° E. is a second major structure trend

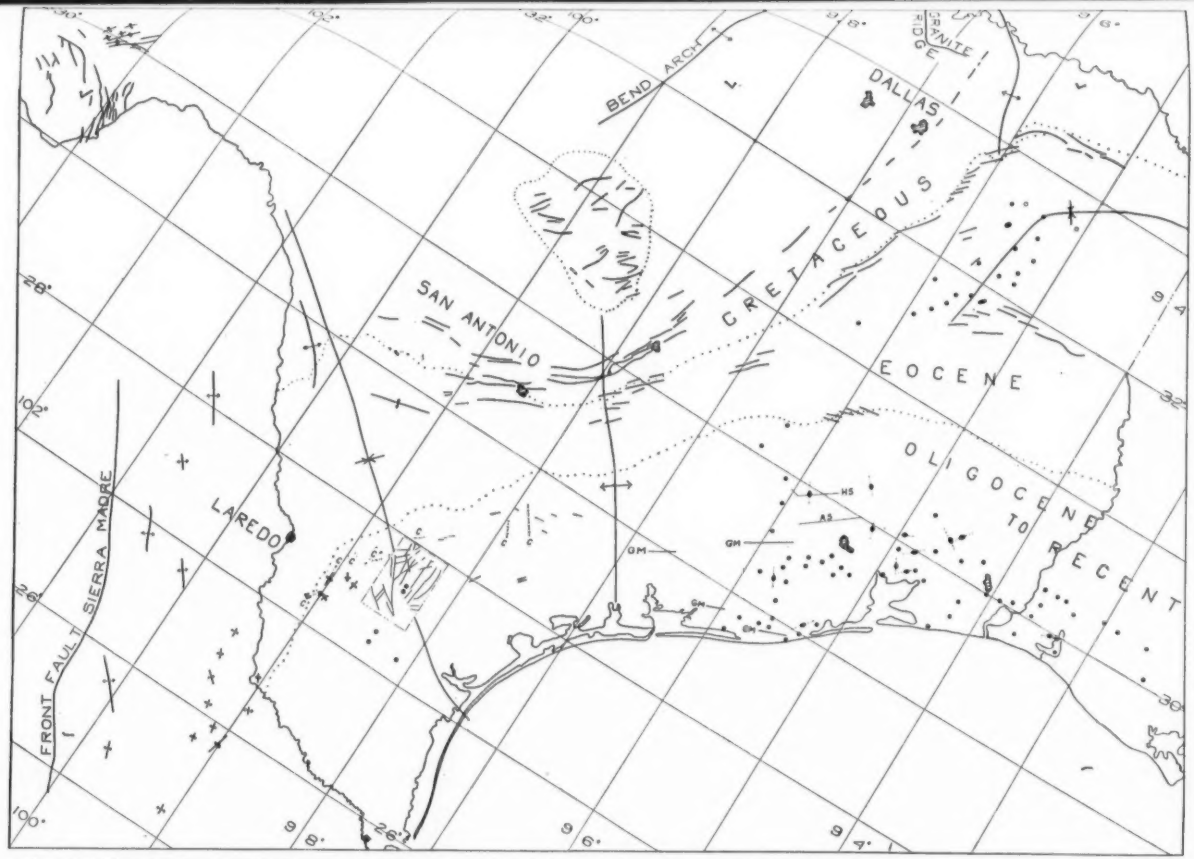


FIG. 6.—Map showing structural trends of southeastern half of Texas and northeastern Mexico. *HS:* Hockley scarp. *AS:* Addicks scarp. *GM:* gravity minima. *C:* zone of chalcedonic mineralization. Solid circles and ellipses: salt domes.

in the southeastern half of Texas. The two areas of early Paleozoic and pre-Cambrian rocks, the Marathon Mountains, and the Llano-Burnet uplift show the trend. The strike of the sharp compressive folding and of the faulting in the Marathon Mountains is northeasterly. The strike of the numerous faults of the Llano-Burnet uplift predominantly is northeasterly. The strike of the faults of the Balcones-Luling-Powell series is northeasterly but that strike may be due to wholly or nearly independent causes. Most of the salt domes of the East Texas geosyncline lie on two parallel lines with a strike of N. 40° E. Alignment of the Gulf Coast domes along northeast-southwest fracture lines was postulated by Harris but is not as clear as it used to be before so many new domes were discovered. However, the salt domes seem to be readily separated into two groups with a strike of N. 50°–55° E. More clearly indicative of the trend is the slight but definite elongation of some of the domes northeast and southwest, for example, Stratton Ridge, North Dayton, South Liberty, Lost Lake, Saratoga, and Old Hackberry. Perhaps more significant are the linear gravity minima which are common in the area south of Houston. A few of them are shown in Figure 6, and are marked *GM*. Those gravity minima have a strike of N. 50°–65° E. The Hockley scarp in Harris County (*HS*, Fig. 6), which is tentatively interpreted by the writer as a fault scarp, likewise has a strike of N. 55° E. The very much less pronounced Addicks scarp in Harris County, which the writer likewise tentatively postulates to be a fault or flexure scarp, likewise has a strike of N. 55° E. (Fig. 6).

The north-south trend is not a common trend, but the alignment of the domes, Palangana, Piedras Pintas (both 27° 40′ N. Lat., 98° 25′ W. Long.), Palo Blanco[6] (27° 15′ N.), and Alta Verde[6] (27° 10′ N.), suggests that it is a deep trend which affects the beds immediately overlying the mother salt bed of the Rio Grande embayment. The parallelism between that salt-dome line and the predominant north-south series of fractures is striking. Some of the oil-field structures of the Mirando district show the north-south trend.

The three major fracture series, therefore, are not superficial features, but reflect deep fundamental structural trends.

BASEMENT STRUCTURES VERSUS STRUCTURES WHOLLY IN UNCONSOLIDATED SEDIMENTS

Two different classes of fundamental structures may be present in the unconsolidated sediments of the Gulf Coast: (1) those which

[6] Not fully established as domes; the seismic method indicates a domed uplift; the torsion balance suggests a deep dome; the drilling data are interpreted as indicating doming.

affect only the thick prism of unconsolidated sediments; and (2) those which have their origin in the basement and which affect both the basement and the overlying unconsolidated sediments.

Tension faults and fractures wholly within the prism of unconsolidated sediments of the Coastal Plain should be expected. Those sediments are unsupported at the edge of the continental shelf; the edge of the continental shelf has a vertical relief of 10,000 feet. Its slope is very gentle but, nevertheless, the dip of the stratification is gulfward; the whole section is water-soaked; many clays are present in the section; and movement can take place along an inclined wet clay surface of very low slope. Slight flowage of the sediments toward their unsupported edge at the edge of the continental shelf should take place and should produce tension along the lines of flowage. Faults and tension fractures should tend to form at right angles to the lines of flowage. The prism of unconsolidated sediments wedges out up the edge of the underlying structural basin of more consolidated rocks. The seaward mass of the sediments should tend to tear away from the inner end of the wedge and form a peripheral line of faults much in the same way that the main snow-ice mass in a cirque tends to pull away from the rock walls to form the bergschrund. The Groesbeck-Mexia-Powell-Sulphur River line of faults and the Cherokee-Anderson County line of faults look as if they were such bergschrund-like lines of faulting. That latter line of faulting lies immediately back of the line of the beginning of the great gulfward thickening of the lower Eocene. The Hockley scarp lies along the line of the beginning of the great thickening of the Pliocene-Miocene-Oligocene section and may belong to that same type of faulting. The Luling fault can not be of that type. Pre-Cambrian gneiss is upthrown under the oil field. The Luling fault, therefore, must be one which originates in the basement and which affects both the basement and the overlying prism of unconsolidated sediments. A northeast-southwest strike is common among the faults of the Groesbeck-Powell-Sulphur River series and of the Cherokee-Anderson County series, although the faults in general are diagonal to the strike of the fault zone. The *en échelon* character of those faults can be explained in several ways, by torsion, by shearing, but possibly also by yielding which has taken place along independent pre-existent northeast-southwest fracture lines.

The northeast-southwest trend belongs to the second class of structures which originate in the basement and which affect both the basement and the overlying prism of unconsolidated sediments. It is the trend of the Marathon Paleozoic folding; it is present in the Llano-Burnet uplift; it involves pre-Cambrian gneiss at Luling.

The northwest-southeast trend also is one of the basement trends. It is the pre-Cambrian trend of the Central Mineral region of the axis of the Rio Grande geosyncline (29° 30′ N. Lat., 97° 30′ W. Long., to 29° 30′ N. Lat., 101° W. Long.), of the Llano-Goliad arch (30° 30′ N., 98° 30′ W., to 28° 30′ N., 96° 45′ W.), and of the Sierra Madre of northeastern Mexico.

The north-south trend of the Palangana-Alta Verde salt-dome line presumably also must be a deep trend, for some north-south structural feature in the mother salt beds and the immediately overlying beds must have controlled the formation of those four domes along a common line.

CAUSE OF FRACTURING

The immediate cause of the surface fractures of three main systems probably is shearing, torsion, or tensional rupture of the caliche and, in places, of the Goliad sandstone. In the supposedly slightly elastic and ductile clayey formations, fractures should not form so easily; and if fractures or fissures formed in sands or clays, the two sides should heal quickly; and the fracture should be obliterated and cease to be a line of weakness. The more consolidated, weak, but presumably inelastic caliche limestones and the weak Goliad sandstones should fracture easily; fractures should not heal easily or quickly and should be zones of weakness along which erosion will take place more easily than in the inter-fracture areas. The greater ease with which the caliche, weak sandstone, and limestone fracture, and the greater ease with which fractures and fissures heal in very unconsolidated sediments explains the restriction of the fracture drainage primarily to the area of the caliche.

The underlying cause of the fracturing presumably is shearing along ancient fractures in the basement, although tension in the direction perpendicular to the strike of the formations may have aided in the formation of the north-south series of fractures.

The tension which should be produced in the Tertiary sediments by their unsupported front at the edge of the continental shelf, at first was thought by the writer to be the primary cause of the fracturing. Further study indicates that such tension is not the primary cause of the fracturing. The close parallelism, and possible connection, of the fracturing with the trends in the basement and in the deep-seated pre-Upper Cretaceous formations had not been recognized. Fractures which are produced by that gulfward tension should tend to parallel the mean strike of the vertical prism of unconsolidated sediments. The mean strike of the sediments within the area over which the frac-

tures can be recognized, from Guadalupe River to the windblown sand area south of Hebbronville, has an appreciable curvature. A corresponding curvature of the strike of the north-south series of fractures has not been recognized. But the individual fracture lines are not geometrical straight lines; and the strike varies slightly from fracture line to fracture line; and a tendency for the mean strike of the north-south fractures to curve correspondingly with the mean strike of the sediments possibly may be obscured by that variability of the strike of the fractures. The strike of the north-south series of fractures in Figure 1 is shown statistically to be between N. 0° and 15° E.; and by symmetry probably to be nearer N. 0° E. than N. 15° E. The strike of the Lagarto contacts across the northwestern quarter of Duval County is N. 33° E.; and the strike of the eastern limit of the caliche is N. 15° E. The strike of the coast opposite northern Duval County is N. 15° E. The strike of the formations in southeastern Webb County is north. Approximately along the east-west mid-line through Duval County, the north strike of the formations in southeastern Webb County bends rather abruptly into the N. 33° E. strike in northern Duval, in McMullen, and in Live Oak counties. The north-south fracture system is best developed in northern Duval County and in the southern edge of McMullen County, although it seems also to be present in the area of Goliad outcrop southwest of George West, and although it extends south to the edge of the area of windblown sand south of Hebbronville. In southern Duval County, the north-south fractures are parallel with the strike of the sediments, but the strike of the fractures does not change northward; and in northern Duval and southern McMullen counties, they are appreciably at an angle to the strike of the sediments. The fractures, furthermore, are somewhat long, straight, and sharp for purely tension fissures. The tension from seaward yielding of the sediments, therefore, is presumably not the primary cause of the fracturing.

The stresses which have produced the shearing are not clearly evident from the available data. Several different stresses could have produced the observed fracture pattern. A north-south, non-rotational compression would produce diagonal northwest-southeast and northeast-southwest planes of shear and a north-south set of tension fissures. A northwest-to-southeast stress increasing southwestward in intensity of the movement would produce rotational strain with the same set of shear and tension planes. Similarly a southwest-to-northeast stress decreasing northwestward in intensity would produce non-rotational strain and the same set of shear and tension planes. The most evident stress which has been active since the formation of the

caliche is the vertical stress which is associated with the subsidence of the coast area. Generally continuous subsidence has been going on at the coast since sometime before the formation of the caliche, and decreases inland; and, presumably, there has been slight uplift in the caliche area. The vertical stress of the subsidence should produce a rotational strain with a horizontal set of shear planes, a vertical set of shear planes parallel with the coast, and a set of tensional fissures parallel in strike with the coast, and dipping inland. That vertical stress, however, would not produce northwest-southeast or northeast-southwest shear planes.

Several independent, not necessarily simultaneous stresses rather than a single stress may be the cause of the surface fractures. There may have been vertical or horizontal shearing along the ancient fractures in the basement. Gulfward tension from the northeast-southwest or northwest-southeast shearing may be supplemented by the gulfward tension from flowage of the sediments toward their unsupported gulfward edge, or from the vertical shearing of the coastal subsidence.

In the Munich Tertiary basin of Bavaria, geodetic re-measurement of older lines has shown shearing of the present surface and has mapped the pattern of the movement. It would be most interesting to have similar measurements in this area to determine whether shearing of the present surface still continues and, if so, in what direction.

The fracture system of South Texas has been shown by this study to be connected with fundamental structural trends of the southeastern half of Texas and northeastern Mexico. Those fractures indicate some sort of movement along those old trend lines since the end of the Pliocene and possibly fairly late in the Pleistocene. But what that movement or those movements may have been and what the full significance of that fracture system may be, have not been revealed by the present study. The full possibilities of the data which can be obtained have not been exhausted. A certain areal variation of the pattern of the fracture lines has been noticed but has not been studied. The areal variation, if any, of the fracture pattern should be but has not been studied. A study of the faults of the area might indicate the dip of the fracture planes and give some clue to the stresses which have produced the fractures. They seemingly are closely connected with the fundamental tectonics of the area, and seem well worth further study.[7]

[7] The writer disclaims any wish to preëmpt further study of these fractures; he would be glad to have a trained research man continue the subject or he would be glad to coöperate with a younger man in further study of the problem.

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SUBSURFACE CONCENTRATION OF CHLORIDE BRINES[1]

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ABSTRACT

In this paper an effort is made to discuss critically the evidence regarding all the processes which may have produced chloride brines more concentrated than sea water. The hypothesis that the concentration is due to evaporation in natural gas is tested by estimating the thicknesses of bituminous shale necessary to produce the required volumes of gas. The possibility of a gravitational settling of the molecules of the chlorides, and the effects of osmosis, hydration, and adsorption are also considered.

The writer deals only with the concentration of the chloride radicle of the brines. The exchange of bases, and the processes affecting the other acid radicles, are not mentioned.

INTRODUCTION

In many regions chloride brines which are much more concentrated than sea water have been found in horizons not closely associated with salt deposits. The origin of these brines is one of the unsolved problems of geology. The purpose of the writer is to discuss critically the various hypotheses that have been proposed to account for the concentration of these brines, and to consider several new theories here proposed.

PREVIOUS THEORIES

No doubt some sediments are deposited in concentrated brines formed by the evaporation of sea water at the surface. However, fossil shells are found in many of the rocks now containing the concentrated chloride brines, and these rocks could not have been laid down in such concentrated solutions, for animals can not live in them, as Barnes[3] has noted. The brines in strata traversed by igneous intrusions or metalliferous veins may have obtained some of their chlorides from deep sources. In some cases, however, the brines have evidently not come from below, for the solutions in the lower horizons are less concentrated. Some of the occurrences of concentrated brines, for example those described by Barnes,[4] are in areas where there are no salt

[1] Manuscript received, July 3, 1933.

[2] 430 Temple Street.

[3] V. E. Barnes, "Oil-Field Waters of North-Central Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 4 (April, 1932), p. 410.

[4] *Op. cit.*, pp. 410–11.

deposits. The hypothesis that the brines have formed by the solution of salt deposits, or by diffusion from solutions that have dissolved salt deposits, can of course not be evoked to explain such occurrences. Moreover, even in areas where salt deposits are present, it is very doubtful whether diffusion could cause the salts to penetrate to porous horizons separated from the salt deposits by impervious shales and limestones. Reeves[5] states that in parts of the Appalachian region there are between the salt deposits and the concentrated solutions deposits devoid of water across which diffusion is impossible. The lenticular sandstones containing less concentrated solutions which lie between the salt deposits and some of the concentrated brines also indicate that in many cases at least the salt did not migrate from the salt deposits by diffusion.

THEORY THAT BRINES ARE CONCENTRATED BY EVAPORATION IN GAS

The theory of Mills and Wells[6] that brines have been concentrated by evaporation in expanding natural gas deserves careful analysis, because it has been accepted by many geologists. This hypothesis may best be tested by calculating the thickness of bituminous shale necessary to produce sufficient gas to cause a concentration of the brine by evaporation. Of course rocks vary enormously in the amount of gas they are capable of producing, but the Chattanooga shale is selected to serve as an example, for a thick body of shale as bituminous as this is not likely to pass unnoticed. According to Crouse[7] the Chattanooga shale will produce 3,000–4,000 cubic feet of gas per ton. Trask[8] has recently made a large number of tests of the volume of gas produced by various sediments. The sample producing the greatest amount of gas was an algal deposit which Trask considered the mother rock of an oil shale. It produced 4,000 cubic feet per ton, or about 130 cubic feet of gas per cubic foot of rock.

The concentration of the brines varies greatly. Brines having a concentration twice that of sea water are of common occurrence, and some have a concentration five times that of sea water. The maximum

[5] Frank Reeves, "Origin of the Natural Brines of Oil Fields," *Johns Hopkins University Circ.* (1917), p. 67.

[6] R. Van A. Mills and R. C. Wells, "The Evaporation and Concentration of Waters Associated with Petroleum and Natural Gas," *U. S. Geol. Survey Bull. 693* (1919).

[7] C. S. Crouse, "The Oil Shales of Kentucky," *Kentucky Geol. Survey Series VI*, Vol. 21 (1925), p. 62.

[8] P. D. Trask, *Origin and Environment of Source Sediments of Petroleum* (1932), p. 285.

concentration mentioned by Barnes[9] is seven times that of sea water.

Assuming that 130 cubic feet of gas is generated per cubic foot of rock, the thickness of bituminous shale necessary to alter the concentration of sea water in a sandstone 50 feet thick and of 20 per cent porosity will be calculated as a test case. The thickness and porosity are of course greater than that of some reservoirs, but on the other hand in many places in a limited vertical section there are a number of horizons containing concentrated brines. In order to make the conditions favorable for the theory, it will be assumed that all the gas generated by the shale reaches the reservoir rock, and that the gas

TABLE I

THICKNESSES OF BITUMINOUS SHALE CONCENTRATE SEA WATER BY EVAPORATION IN GAS

Geothermal Gradient in Degrees F.	*Depth in Feet*	*Temperature, Degrees F.*	*Assumed Pressure, in Atmospheres*	*Thickness in Feet of Bituminous Shale Required*	
				Concentration Twice that of Sea-Water	*Concentration Five Times that of Sea-Water*
1° to 30 ft.	9,000	370	250	2,200	8,800
"	3,600	190	100	16,000	65,000
"	1,800	130	50	33,000	130,000
"	900	100	25	40,000	160,000
1° to 60 ft.	9,000	220	250	25,000	100,000
"	3,600	130	100	68,000	270,000
"	1,800	100	50	80,000	320,000
"	900	85	25	80,000	320,000
1° to 90 ft.	9,000	170	250	63,000	250,000
"	3,600	110	100	120,000	480,000
"	1,800	90	50	110,000	440,000
"	900	80	25	75,000	300,000

contains no moisture on reaching it. The fact that a gas in contact with a brine can hold less moisture than when it is in contact with fresh water will also be neglected. The temperature of the surface is assumed to be 70° F.

Data regarding the moisture content of gas at various temperatures are given by Mills and Wells.[10]

The figures in the right-hand columns of Table I show that even if the gas contained no moisture on entering the water horizons, the thicknesses of bituminous shale required to produce concentrated brines by evaporation are generally so enormous as to be entirely out of the question. Most of these thicknesses are, in fact, greater than

[9] V. E. Barnes, *op. cit.*, p. 410.

[10] R. Van A. Mills and R. C. Wells, *op. cit.*, p. 82.

the thicknesses of the entire sedimentary columns of the areas in which the brines occur. Only where the geothermal gradient is approximately 1° F. per 30 feet of depth and the depth is approximately 9,000 feet or more do the required thicknesses of bituminous shale even approach the actual.

It should, however, be remembered that the data in Table I have been calculated on the assumption that the gas contained no moisture on entering the water horizon. This could of course occur only where the strata previously traversed were devoid of water. As the pore space of shales is generally filled with water, the gas would inevitably contain some water on leaving them, and if the water in the pore space was greater than the volume of water which the gas generated in the shales could hold, the gas would be saturated with moisture on leaving the source rock. In order to determine the moisture content of the gas on entering the reservoirs containing the brines, it is therefore necessary to compare the volume of water, which the gas produced by a given volume of shale is capable of evaporating, with the volume of water in the pore space of the shale. In Table II the volume of water at saturation contained in the gas produced by a given volume of bituminous shale is shown expressed as percentages of the volume of the shale. It is assumed that the geothermal gradient is 1° F. for 30 feet of depth, that a cubic foot of the bituminous shale produces 130 cubic feet of gas, and that the temperature at the surface is 70° F. If the geothermal gradient was less than this, the quantities of water which the gas could hold would of course be much smaller.

TABLE II

Depth in Feet	*Temperature, Degrees F.*	*Assumed Pressure in Atmospheres*	*Water at Saturation Contained in Gas Produced by Given Volume of Shale, Expressed as Percentage of Volume of Shale*
9,000	370	250	0.44
3,600	190	100	0.061
1,800	130	50	0.029
900	100	25	0.025

Athy[11] has represented graphically the relation between the depth and porosity of shales, and Hedberg[12] has presented another depth-porosity curve which shows much higher porosities at great depths.

[11] L. F. Athy, "Density, Porosity, and Compaction of Rocks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 1 (January, 1930), p. 13.

[12] Hollis D. Hedberg, "The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 11 (November, 1926), p. 1058.

According to Athy's data, the porosity of shales would be about 20 per cent at a depth of 2,000 feet, and slightly less than 2.5 per cent at a depth of 7,000 feet. At a depth of 9,000 feet the porosity would presumably be nearly 2 per cent. As most shales contain water when deposited, and as the decrease of porosity with depth is produced largely by the expulsion of excess water, the pore space of shales is probably generally filled with water. Hence, at a depth of 9,000 feet the volume of water in a shale should be approximately 2 per cent of the volume of the shale. According to Table II, at a depth of 9,000 feet the volume of water which the gas generated in the shale could hold would be only 0.44 per cent of the volume of the shale, even with a geothermal gradient of 1° F. for 30 feet of depth, and at lesser depths the porosity of the shale would be greater and the volume of water in the gas even less. Because at the depths covered by Table II the volume of water in the shale is in every case considerably greater than the volume of water the gas developed in the bituminous shale could hold, the gas would leave the shale saturated with water, and consequently would be unable to evaporate any moisture in the water horizon on entering it directly from the shale.

It might be supposed, even if the gas was saturated with water on leaving the bituminous shale in which it formed, that the expansion during its ascent toward the surface would permit the evaporation of additional water. As the amount of water which a given volume of gas can hold is practically unaffected by the pressure, if the temperature remained the same the volume of water in a given mass of gas at saturation would be inversely proportional to the pressure. However, as the gas rises the temperature decreases; consequently, each cubic foot of gas could hold less water vapor. If a given mass of gas be imagined originating at a depth of 9,000 feet and moving upward, and if the temperatures and pressures were the same as assumed in Table I, the volumes of water per cubic foot of the saturated gas at the various depths would be inversely proportional to the figures in the right-hand columns of Table I. Since for temperature gradients of 1° F. to 30 feet and 1° F. to 60 feet, these figures increase as the depth decreases, the given quantity of gas could hold less and less water as it approached the surface. In other words, some of its original content of moisture would be precipitated. This is because the effect of the decrease in temperature is greater than the effect of the larger volume. At very shallow depths, this is reversed, and the gas could evaporate moisture instead of precipitating it. The more rapid the increase in temperature with depth, the shallower the depth at which this reversal takes place. Where the geothermal gradient is 1° F. for each

90 feet of depth, which is less than the average, the reversal occurs at the depths shown in Table I, and the rising gas at depths less than 3,600 feet would evaporate additional water. However, as Table I shows, the thicknesses of shale required to produce any considerable degree of concentration by this evaporation are impossibly large, and they would be even larger than the thicknesses shown in Table I, because the gas would have contained considerable moisture when it reached the depth at which the reversal took place.

The effect of evaporation in natural gas at very shallow depths remains to be considered. This evaporation may have taken place close to the present surface, close beneath previous erosion surfaces marked by unconformities, or in strata which had not yet been deeply buried. If the water horizons were persistent, gas rising through them might concentrate the brine by evaporation close to the outcrop, and this heavier concentrated solution might settle down the dip to the lowest parts of the reservoir.

At very shallow depths concentration by this method would not be effective, because waters very close to the surface are generally mixed with fresh meteoric water. Let it be assumed that the water horizon was 50 feet thick and its porosity 20 per cent, that the evaporation took place at a depth of 360 feet at a pressure of 10 atmospheres and a temperature of 80° F., and that the bituminous shale produces 130 cubic feet of free gas per cubic foot. It would then require a body of bituminous shale 30,000 feet thick to double the average concentration of the brine in the reservoir, even if all the gas was effective in producing the concentration, and all the evaporation took place in the reservoir. It is therefore evident that occurrences of concentrated chloride brines covering any considerable area could not have been concentrated in this manner.

If the gas from a great area of bituminous shale should pass through small, isolated bodies of salt water at very shallow depths, highly concentrated solutions might be formed. For example, if the same assumptions are made as in the previous paragraph, it would require all the gas from a bed of the bituminous shale 100 feet thick covering an area 300 times the area of the body of the salt water to double its concentration by evaporation. This indicates that only small, scattered occurrences of concentrated chloride brines could be formed by evaporation into natural gas at shallow depths.

The concentrated chloride brines might have been developed in the bituminous shales by evaporation in the gas produced by these shales, and these brines might be later forced into the water horizons by compaction. The amount of concentration thus produced would

depend on the ratio of the volume of water which the gas originating in the shale could evaporate to the volume of sea water in the pore space of the shale. According to Table II, the volume of water which could be evaporated by the gas generated in the bituminous shale would be 0.44 per cent of the volume of the shale at a depth of 9,000 feet and with a geothermal gradient of 1° F. in 30 feet of depth. As has been previously explained, it is probable that the porosity of the shale at that depth would be about 2 per cent, and if the pores of the shale were filled with sea water, the solution produced by the evaporation would have a concentration about 1.3 times that of sea water. If the depth or the rate of increase in temperature were less, the amount of increase in concentration produced by the evaporation would be much smaller. On the other hand, at depths greater than 9,000 feet the concentration of the evaporated solution would rise rapidly, and, if the temperature increase was 1° F. every 30 feet, a depth would ultimately be reached at which the gas could evaporate all the water in the pores of the bituminous shale.

It should be remembered that in making the preceding calculations some assumptions have been made which favor concentration by evaporation. Few shales produce as much as 4,000 cubic feet of free gas to the ton. Under natural conditions a shale may not produce as much gas as in a laboratory distillation, and some of the gas would probably have been formed at shallower depths, where its influence would have been slight because of the greater porosity. A geothermal gradient of 1° F. to 30 feet is also greater than the average. The porosity of the shales at great depths is an uncertain quantity, and may be greater than assumed. Furthermore, many of the rocks which contain the concentrated chloride brines have probably never been buried to depths of more than 9,000 feet. Moreover, unless the reservoir containing the brines was associated solely with richly bituminous rocks, the concentrated solutions expelled from the bituminous shales on further compaction would probably be mixed with unconcentrated solutions ejected from the non-bituminous shales at the same time. It may therefore be concluded, though it is theoretically possible that concentrated chloride brines found in rocks that have been deeply buried have been concentrated by evaporation in the natural gas generated in bituminous shales, that it is doubtful if many actual occurrences have been formed in this manner.

In the preceding discussions, it has been assumed that the evaporation takes place at pressures slightly less than the hydrostatic pressure due to the weight of a column of water reaching to the surface. There are of course many occurrences of fluids in porous strata in

which the hydrostatic pressure is considerably less than this. However, the gas pressure in a closed reservoir depends on the amount of gas contained in it. If gas in such great quantities as would be required to produce a concentrated brine by evaporation invaded a closed reservoir, the pressure would rise until it was close to that assumed in the calculations.

If the evaporation took place in open fissures extending to the surface, the pressure would be greatly reduced, and more water could be evaporated than at the pressures assumed in Tables I and II. Gas may of course escape through open fissures when erosion has brought the gas pools close to the surface, but there are good reasons for supposing that crevices devoid of water do not extend through great thicknesses of porous sedimentary rocks. When wells are drilled through such formations, both the surface waters and the water-bearing beds below the surface are cased off. In natural openings there would be no casing, and the water from the surface and from each water horizon would flow into the crevice and fill it with water. Under some conditions, however, the gas pressure might be sufficient to blow the water out of the crevice, and some of the salt water in the same reservoir as the gas pool would then evaporate in the expanding and escaping gas. If the volume of the salt water in the reservoir was the same as the volume of the gas pool, the concentration due to this evaporation would be so small as to be negligible. If, for example, the depth of the gas pool was 3,600 feet, the pressure 100 atmospheres, and the temperature 190° F., the concentration of the salt solution by evaporation into this escaping gas could be considerable only if the volume of the salt water in the reservoir was less than 0.01 of the volume of the gas pool.

As a result of the analysis of the evidence bearing on the theory that concentrated chloride brines have been formed by evaporation in natural gas, the following conclusions may be drawn. The extensive occurrences of these chloride brines did not originate by evaporation in the horizons in which they are now found. Only small and unimportant bodies of concentrated brine could have come into existence in this fashion. Though it is possible that under certain conditions concentrated brines could have been expelled from bituminous shales into reservoirs closely associated with them at great depths, it is doubtful if many of the known occurrences could have been generated in this manner. The evidence in general favors the conclusion that some other process has produced the concentration.

CONDENSATION IN CAPILLARY PORES

If a rock containing very fine pores, such as a clay or shale, is in contact with gas saturated with moisture, water will be condensed in the pores. If the same body of gas is in contact with a water surface in a coarse-grained rock, such as a sandstone, water evaporating in the sandstone might be transferred to the shale. Washburne[13] thinks this process may have been effective in producing concentrated brines.

This action, however, could take place only in a formation containing gas pools, and there is no reason to suppose that the concentrated brines occur solely in association with gas. Moreover, the transfer of the water from the coarse-grained reservoir to the shale could occur only if the gas body extended into the shale. According to the generally accepted theories of capillarity, this would be impossible. The pores of the shale in contact with the water horizon would be filled with water, and capillarity would prevent the gas from entering the shale. Even if the gas did enter the shale, water drawn into it by capillarity would eject the gas. Even assuming that the gas did extend partly into the shale, the first water deposited would close the fine pores, preventing the continuance of the process. Furthermore, while sediments are being compacted, water is being expelled from them into adjacent water horizons, and any water condensed in the shale might be forced back into the original reservoir again.

EVAPORATION BENEATH FORMER SURFACES

Although the fossil content of many of the horizons containing concentrated brines shows that they were deposited in normal sea water, some of the associated shales may have been deposited in brines concentrated by evaporation at the surface, and this concentrated brine may have been later forced into the water horizons during compaction. Before they were deeply buried, the solutions in the sediments may also have been concentrated by deep evaporation during prolonged periods of aridity. Red shales and other suggestions of aridity indicate that this may possibly have taken place in certain formations.

POSSIBILITY OF CONCENTRATION BY MOLECULAR SETTLING

It is well known that the molecules of solutes behave in many respects like those of gases. In a free gas, such as the atmosphere, the gas pressure must balance the weight of the overlying column of gas,

[13] Chester W. Washburne, "Oil-Field Brines," *Trans. Amer. Inst. Min. Met. Eng.*, Vol. 65 (1921), p. 269.

and in ascending through the atmosphere the gas pressure, and consequently the density, decrease because the weight of the overlying column of air is less. If a gas is at rest the difference in the gas pressure at two levels in the gas is therefore exactly equal to the weight of the column of gas between them. If two gases, one heavier than the other, are mixed in equal proportions in a tall vertical container, the heavier gas becomes more concentrated in the lower part of the container, and this settling of the molecules of the heavier gas continues until the upward decrease in its gas pressure balances the weight of the column of the gas. For this reason, as Soddy[14] has explained, the relative amounts of the lighter gases in the atmosphere increase upward.

In solutions, as Einstein[15] and Freundlich[16] have noted, osmotic pressure has in many respects the same effect that gas pressure has in gases. It is differences in osmotic pressure that cause diffusion from higher to lower concentrations. In solutions, however, the molecules of the solute are buoyed up by the solvent, and, as Rideal[17] has stated, it is the excess density of the solution over that of the pure solvent which must be supported by the increase in osmotic pressure and concentration downward. Hence the increase in concentration downward may be calculated by determining the increase in osmotic pressure necessary to balance the excess density. The density of sea water containing 3.5 per cent of salts is 1.0223 at 76.6° F., and the density of pure water at this temperature is 0.9977. Hence the excess density of the solution which must be supported by the osmotic pressure is 0.0246. The osmotic pressure of sea water, according to the *Encyclopaedia Britannica*,[18] is 23.1 atmospheres. It would require a column of sea water about 32,000 feet high to give an unsupported weight due to the excess density sufficient to balance a pressure of 23.1 atmospheres. As the osmotic pressure of a solution such as sea water increases more rapidly than the concentration, the osmotic pressure of a solution having twice the concentration of sea water would have more than twice the osmotic pressure of sea water, but on the other hand, when equilibrium had been attained, the average density of the solution down to the level where the concentration was doubled would be greater than 1.0223. Hence 32,000 feet may be taken as roughly

[14] F. S. Soddy, *The Interpretation of the Atom* (1932), p. 274.

[15] A. Einstein, *The Investigation into the Theory of the Brownian Movement*, translated by A. P. Cooper (1911), p. 70.

[16] H. Freundlich, *Colloid and Capillary Chemistry*, translated by H. S. Hatfield (1924), p. 70.

[17] E. K. Rideal, *An Introduction to Surface Chemistry* (1930), p. 369.

[18] *Encyclopaedia Britannica*, 14th ed. (1929), Vol. 16, p. 686.

representing the height of the column of sea water necessary for a doubling of the concentration by a settling of the solute molecules.

Many of the rocks in which concentrated chloride brines are found have probably never been buried to a depth of 32,000 feet. Moreover, concentration by gravity could occur only where the water-bearing horizon was continuously pervious through a great vertical distance, and this theory could not account for the occurrences of concentrated brines in lenticular deposits. It therefore appears, if the correct method has been used to calculate the increase in concentration with depth, that concentrated chloride brines can not have been formed by the gravitational settling of the solute molecules.

CONCENTRATION BY HYDRATION

It has often been suggested that the concentration of brines has been increased by the absorption of water in the hydration of minerals. Hydration is most active in the zone of weathering near the surface, and as the minerals of shales and sandstones have passed through this zone, it might be supposed that they would already have been decomposed by chemical agencies at the surface, and could absorb no additional water after burial. This would probably be true of shales and sandstones which were the products of a type of erosion permitting thorough decomposition of the minerals, but if the conditions favored disintegration rather than decomposition, the resultant shales and sandstones might contain considerable undecomposed material. Glacial deposits and deposits derived from erosion in arid climates would doubtless be of this nature. Arkose, for example, consists largely of undecomposed feldspar, and according to Hatch and Rastall,[19] feldspar is an important constituent of some shales. If sediments of the geologic past are found on examination to contain no undecomposed minerals, this does not indicate that such minerals were not present on deposition, for they may have been destroyed by hydration after burial.

Though it is difficult to secure quantitative data showing what fraction of the shales and sandstones associated with the concentrated brines consist of minerals formed by hydration, the fact that some sedimentary rocks contain considerable amounts of minerals capable of hydration indicates that the possibility of the concentration of brines by hydration must be recognized. Moreover, thin sections of some arkoses and sandstones furnish definite evidence that some

[19] F. H. Hatch and R. H. Rastall, *The Petrology of the Sedimentary Rocks* (1913) p. 195.

hydration has occurred after burial, for they indicate that feldspars have been replaced by various fine-grained alteration products. As noted elsewhere,[20] thin sections of feldspathic sandstones obtained by the writer in West Virginia show that the feldspars have been decomposed and that the fine material thus produced, consisting probably of such minerals as chlorite, sericite, quartz, epidote, and kaolin, fills the space between the original grains of the sandstone. Sandstones and arkoses the minerals of which have been subjected to extensive hydration are probably too impervious to yield much brine when penetrated by the drill. Hence it is probable, if concentrated chloride brines have been produced by hydration, that the concentration has taken place in rocks other than those in which the brines are now found, and the concentrated solution has been forced into the reservoirs during the compaction of the sediments.

In the hydration of the feldspars and other unstable minerals considerable volumes of water would be absorbed. According to Bayley,[21] the feldspars generally contain less than 1.0 per cent of water, though of the hydrated minerals produced by decomposition muscovite contains about 5.5 per cent of water, kaolin approximately 13 per cent, the minerals of the chlorite group 9–14 per cent, and epidote about 1.9 per cent. If, for example, hydrated minerals comprising 20 per cent by weight of a shale of 2.5 specific gravity were produced, and if the water absorbed was 8 per cent of the weight of the hydrated minerals, the volume of the water absorbed would be 4 per cent of the volume of the shale. If the pores of the shales contained sea water, highly concentrated chloride brines would be produced in shales of low porosity by the absorption of this volume of water.

EFFECT OF OSMOSIS

Osmosis is ordinarily thought of as occurring when a semi-permeable membrane separates a dilute from a concentrated aqueous solution, the membrane being permeable to the solvent but not to the solute. When these conditions are fulfilled, osmosis, according to the common conception, causes water to be drawn through the semi-permeable membrane into the concentrated solution, until the increase in the osmotic pressure of the concentrated solution stops the process. Osmosis may, however, be negative as well as positive. In negative osmosis water would be forced from the concentrated to the dilute solution.

[20] W. L. Russell, "Porosity and Crushing Strength as Indices of Regional Alteration," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 10 (October, 1926), p. 939.

[21] William S. Bayley, *Descriptive Mineralogy* (1917), pp. 413, 355, 405, 328.

According to Findlay,[22] osmotic effects have been obtained in the absence of a membrane with pore diameters of 0.5 micron, which is larger than the diameters of the pores of some clays and shales, and according to Freundlich[23] and Demolon and Barbier[24] clays have some osmotic properties. If osmosis occurs in the fine-grained rocks associated with water-bearing horizons, it might conceivably be either positive or negative. That is, water might be drawn into the fine-grained rocks, leaving the solution in the water horizons more concentrated, or it might be expelled from the fine sediments, leaving a concentrated solution in them. This concentrated solution might later be expelled into the porous reservoirs by compaction, recrystallization, heat, or other processes which would reduce the porosity or the osmotic properties of the shales. Thus the concentrated solutions might eventually find their way into the reservoirs in which they are now found. Osmotic reactions might also take place between the fine sediments and the sea water, while the deposits lay at the bottom of the sea before burial, and if chlorine or chlorides were concentrated in the fine materials by this process, they might be later expelled into the reservoirs containing water.

Though it is clear that clays and shales have some properties which resemble those of membranes, sufficient data are not available to show exactly how these would affect the concentration of chloride brines in associated rocks. At present all that can be confidently stated is that such properties may have had an important effect on the concentration of these brines, and that this subject offers a promising field for further research.

CONCENTRATION BY ADSORPTION

It has long been known that clays and very fine-grained soils will adsorb salts from solution. The amount adsorbed is probably proportional to the total surface area of all the particles in the material. Since the total surface area of very fine-grained rocks is enormously greater than that of coarse-grained rocks, it is evident that adsorption would be important only in the fine-grained rocks, and in a given sediment the finest portion would contain nearly all the adsorbed salts.

In some cases, at least, it is believed that only the basic ion of the

[22] Alexander Findlay, *Osmotic Pressure* (1913), p. 67.

[23] H. Freundlich, *Colloid and Capillary Chemistry*, translated by H. S. Hatfield (1926), p. 268.

[24] A. Demolon and G. Barbier, "Adsorption ionique dans l'argile colloidale," *Comptes Rendus*, Vol. 185 (1927), pp. 149–50.

salt is adsorbed. The acid radicle is held more loosely, and in some cases may be set free. According to Harris,[25] soils which have adsorbed the basic ion of the salt from solution give an acid reaction. If these soils are immersed in pure water, they will give an acid reaction with litmus, but only when the soil is actually brought into contact with the litmus. If the soil is mixed thoroughly with the pure water and allowed to settle, no acid can be detected in the water. When, however, the soils are mixed with a solution of a neutral salt, the acid is gradually set free, and may be detected in the solution.

For the present purposes, the weight of sodium chloride withdrawn from solution by the adsorption may best be expressed as percentages of the weight of the adsorbed material. In the experiment of Demolon and Barbier[26] on colloidal clay isolated from brick clay, this weight was 2.1 per cent of the weight of the clay, while in work on soils described by Harris[27] it was 0.07 per cent. Bremond[28] has calculated that a colloidal clay having an average diameter of 0.1 micron would adsorb a weight of sodium chloride equal to 2.88 per cent of the weight of the clay. This, however, is finer than the average shale. Trask[29] states that the diameters of the grains of a clay generally range from 1 to 5 microns.

Very fine sediments laid down in sea water should contain considerable adsorbed bases, but it is not clear whether the chlorine would accompany these bases, or whether all or a portion of it would be released and escape before burial. If some or all of the chlorine remains in the marine deposits, certain agencies, such as recrystallization, cementation, and the effects of heat and pressure, may cause the liberation of the adsorbed materials as chlorides. The effect of these agencies should increase with depth. As most of the adsorbed salts or ions are held on the finest particles of the sediment, and as the finest grains are the first to recrystallize into larger masses, it is obvious that recrystallization would liberate most of the ions or chlorides held on the surfaces by adsorption. The chlorides thus released would increase the concentration of the solutions occupying the pore

[25] J. E. Harris, "Some Adsorption Phenomena in Soils and Kaolin," *Jour. Phys. Chem.*, Vol. 18 (1914), p. 354.

[26] A. Demolon and G. Barbier, *op. cit.*, p. 149.

[27] J. E. Harris, *op. cit.*, p. 389.

[28] P. Bremond, "The Adsorbing Power of Clays and Its Influence on Their Content of Alkalies and Other Substances," *Revue des Materiaux de Travaux Publics*, Vol. 195 (1925), pp. 271–73, reviewed in *Chemical Abstracts*, Vol. 20, Pt. 2 (1926), p. 1892.

[29] P. D. Trask, *Origin and Environment of Source Sediments of Petroleum* (1932), p. 70.

spaces of the rocks, and after further compaction they might be expelled into the associated water-bearing horizons.

Until more definite knowledge is available regarding the amounts of chlorides that are adsorbed during the deposition of fine sediments in sea water, it is difficult to apply a quantitative test to this theory. However, if, for example, a quantity of sodium chloride amounting to 0.1 per cent of the weight of a shale were expelled without accompanying water into a reservoir containing sea water and having a thickness of 50 feet and a porosity of 20 per cent, it would require a stratum of shale only 140 feet thick to furnish enough salt to double the concentration of the solution in the reservoir. A bed of shale 560 feet thick would furnish enough salt to raise the concentration to five times that of sea water.

However, before the salts released from adsorption could reach the water horizons, they would mix with the solutions already occupying the pores of the fine-grained rocks. If the pores of these rocks contained sea water and the porosity was 2 per cent, the addition of a quantity of adsorbed salts equal to 0.1 per cent of the weight of the rock would give a solution having about 4.6 times the concentration of sea water, and if the porosity was 10 per cent the resultant solution in the pores would have a concentration about 1.6 times that of sea water. The solutions expelled from these fine-grained rocks into the water horizons would differ considerably in concentration, because of differences in the fineness and porosity of the rocks from which they came, and the heaviest and most concentrated solutions would tend to settle towards the lowest parts of the reservoir.

If it could be shown that sufficient quantities of chlorine are entombed with the fine sediments as a result of adsorption, this theory would be very promising. Until further investigations have furnished additional information bearing on this point, it is difficult to estimate the importance of adsorption in producing concentrated chloride brines.

CONCLUSIONS

1. The evaporation of water into natural gas has not been an important factor in producing concentrated chloride brines, although it is possible that some of these brines have been generated in this manner in richly bituminous rocks that have been buried to great depths.

2. The evaporation of water in coarse-grained rocks and its precipitation in very fine pores has probably been of little importance.

3. Under some conditions brines may have been concentrated after deposition by deep evaporation during periods of prolonged aridity.

4. Although settling of solute molecules probably occurs, its effect is presumably too slight to be of importance in producing the known occurrences of concentrated brines.

5. Certain rocks contain large amounts of unstable minerals, and in such formations there may have been considerable concentration by hydration.

6. Though osmosis may have had an important influence on the concentration of brines, too little is known about its action in sedimentary rocks to justify any positive statement.

7. It is probable that the bases of chloride brines are adsorbed from sea water in considerable quantities by very fine sediments during deposition, and if the chlorine is also entombed in these sediments, adsorption may be a very important agency in the subsurface concentration of chloride brines.

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GENERATION OF OIL IN ROCKS BY SHEARING PRESSURES. IV-V. FURTHER STUDIES OF EFFECTS OF HEAT ON OIL SHALES[1]

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ABSTRACT

This is a report of research conducted in 1930–31 in the geological laboratory of the University of Wisconsin as a project of the American Petroleum Institute. Results of previous studies on the generation of oil in rocks by shearing pressures have been published in earlier numbers of this *Bulletin*. Those earlier phases of the work have shown that slightly larger amounts of soluble organic matter may be extracted from shales that have been subjected to shearing pressures at room temperature than can be recovered from unsheared samples of the same materials. The conclusion was reached that, though the change in the amount of extractable organic matter is quantitatively unimportant and may ordinarily be related to physical causes, the effect can not be neglected. Subsequent attempts to discover the effects of shearing pressures on the same materials at temperatures existing at depths of oil accumulation produced conflicting results. The amount of "soluble bitumen" recoverable from samples so treated was less than that from untreated samples. In general, however, the results confirm the observations of other workers. The character and the amount of the products formed by the action of heat on the organic matter of this shale are found to depend on the combined influence of three variable factors: temperature, duration of heating, and the ratio between the volume of organic material and the volume of pore space available to the gases generated as a result of heating.

INTRODUCTION

Additional experiments were made with oil shale during 1930–31 for the purpose of studying the effects produced on its organic constituents by the action of heat. The work forms a part of the investigation listed as Project 1 of the American Petroleum Institute and is in continuation of that previously reported. It was conducted in the geological laboratories of the University of Wisconsin under the guidance of W. J. Mead and with the assistance of helpful suggestions from David White and F. H. Lahee.

In an earlier phase of the work, it was found[3] that slightly larger

[1] Manuscript received, June 10, 1933. This paper contains results obtained in an investigation on "The Generation of Oil in Rocks by Shearing Pressures," listed as Project No. 1 of the American Petroleum Institute Research. Financial assistance in the work has been received from a research fund of the American Petroleum Institute donated by the Universal Oil Products Company. This fund is being administered by the Institute with the coöperation of the Central Petroleum Committee of the National Research Council. W. J. Mead is director of the project.

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[3] J. E. Hawley, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 4 (April, 1929), pp. 329–65, and Vol. 14, No. 4 (April, 1930), pp. 451–81.

amounts of soluble organic matter may be extracted from shales that have been subjected to shearing pressures at room temperature than can be recovered from unsheared samples of the same materials. The conclusion was reached that, though the change in the amount of extractable organic matter is quantitatively unimportant and may ordinarily be related to physical causes, the effect can not be neglected.

Subsequent attempts[4] to discover the effects produced by shearing pressures imposed on the same materials at temperatures such as exist or may have existed at depths within the known range of oil accumulation in the earth produced conflicting results. The amount of "soluble bitumen" recoverable from samples treated in this manner was, in most cases, even smaller than that to be obtained from untreated samples. Somewhat increased recoveries, however, were found to result from the same treatment when applied to materials of a coaly nature. Further tests indicated that the amount of extract recoverable from samples so heated varies not only with the type of specimen and the temperature to which it is subjected, but also with the time during which heating continues and with the conditions under which it takes place. Investigation of the effects produced by these inter-related factors has been continued during the past year.

In order to facilitate the measurement of variables other than those supplied by the shales themselves, experiments have been conducted principally with a single shale. This was collected near Rulison, Colorado, through the courtesy of A. A. Baker, United States Geological Survey, "from the same bed from which most of the Bureau of Mines material was obtained" (presumably from the Green River formation of Eocene age).

The results obtained confirm, in general, the observations of other workers. The character and the amount of the products formed by the action of heat on the organic matter of this shale are found to depend on the combined influence of three variable factors: temperature, duration of heating, and the ratio between the volume of organic material and the volume of pore space available to the gases generated as a result of heating.

Only a small percentage of the organic material in the shale is originally soluble in organic solvents. Conversion of the insoluble portions to a soluble form takes place at a rate depending on the temperature at which the shale is heated. The amount of soluble matter formed depends on the duration of heating. The weight of

[4] W. P. Rand, "Fourth Annual Report," *Amer. Petrol. Inst. Project 1* (1930), unpublished. An annual progress report preliminary to the publication of results in Report No. 4–5.

soluble organic matter extractable from the shale was increased 442 per cent by heating samples for 30 hours in tightly packed bombs at 350° C. and was increased 7 per cent by heating in a similar manner for approximately a month at 150° C. Because of this rapidly diminishing rate of reaction, laboratory experiments conducted at earth temperatures are restricted by the element of time.

Volatilization of both the original and the newly made soluble matter takes place at comparatively low temperatures and proceeds at a measureable rate at 105° C. Its progress is checked by restricting the volume of void space about the material, indicating that devolatilization progresses until sufficient vapor pressure is built up in the surrounding space to prevent further decomposition of organic material.

Strong gas pressures are developed at the higher temperatures, but no specific relation has been observed between volumes of gas and yields of extract beyond the fact that low gas pressures at these temperatures indicate leaky bombs and erratic bitumen recoveries.

PREVIOUS HEAT TESTS WITH OIL SHALES

When heated at temperatures sufficient to cause destructive distillation of their organic constituents, various shales have long been known to yield gases which, on cooling, condense in part to form a crude type of oil. It is only within the last 10 years, however, that systematic study has been made either of the organic matter itself or of its behavior under the influence of heat. Even yet, except for the chemical elements that enter into its composition, but little is known of the chemical structure of the fossil material apart from the fact that it is a hydrocarbon of complex and variable nature.

Recent investigations by the Bureau of Mines and by various individuals, notably R. H. McKee and E. E. Lyder, C. G. Maier and S. R. Zimmerly, and Taisia Stadnichenko and David White have supplied much information respecting the materials which compose the organic substance of the shales, their reactions to heat, and the nature of the products formed. The poorly preserved state of much of the organic matter in the shales as well as the minute size of particles hinders recognition of the individual components. In general terms, the organic materials have been classified as organic detritus and kerogen,[5] the latter being defined as "a less adulterated product than organic detritus, or as an intermediate product between organic detritus and oil." More detailed information has lately been afforded by

[5] Earl A. Trager, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 8, No. 3 (May-June, 1924) pp. 301–11.

Miss Taisia Stadnichenko's[6] microscopic studies of various "source rocks" which have shown that the organic ingredients consist chiefly of the more indestructible parts of plants and animals together with the products of decay of different kinds of plant and animal matter. The portions that can be identified are principally the outer coverings of spores and pollen grains, fragments of the protective skin of various plants, the remains of algae, and pieces of woody tissue and resin.

Oil, as such, has not been formed in measurable quantitities in laboratory experiments with oil shales at the temperatures so far recorded from petroleum-bearing strata. It has been shown, however, that the organic matter in the shales is not converted directly to the form of oil under the influence of heat and that at least the preliminary steps in the process may be initiated at comparatively low temperatures. The experiments of McKee and Lyder[7] demonstrated that "the pyrobitumens do not decompose to form petroleum oils as a primary product of decomposition, but that the first substance obtained is a heavy solid or semi-solid bitumen," and further that, "the petroleum oils formed from the shale are the result of the decomposition or cracking of the heavy bitumen." Maier and Zimmerly,[8] following their discovery that "bitumen" formation does not take place at a definite temperature as was formerly supposed, conducted a series of experiments to determine the rate of "bitumen" formation at temperatures varying from 200° to 365° C. Measurements of the effects produced were made on the basis of the amount of "bitumen" that could be extracted from the samples with carbon tetrachloride solvent. A mathematical expression was derived for calculating the rate of "bitumen" formation at any temperature and for computing the amount of "bitumen" formed during a given period of heating. The conclusion was reached that "the nature of the transformation shows that it does not begin at any definite temperature" and that "the amount of bitumen formed is independent of the temperature provided that the time of heating is long enough." Trask[9] has supplied a correction to this conversion formula. He also notes that much smaller quantities of originally soluble "bitumen" are found in recent sediments than in oil shale of comparable organic content, and that

[6] Taisia Stadnichenko and David White, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 9 (September, 1926), pp. 860–76; Vol. 13, No. 7 (July, 1929), 823–48; Vol. 15, No. 2 (February, 1931), 161–64.

[7] R. H. McKee and E. E. Lyder, *Jour. Ind. & Eng. Chem.*, Vol. 13, No. 7 (July, 1921).

[8] C. G. Maier and S. R. Zimmerly, *Utah Eng. Exper. Sta. Bull. 14* (January, 1924).

[9] Parker D. Trask, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 1 (January, 1931), pp. 83–84.

when recent deposits and oil shales are heated in the same manner, the results are similar.

The Bureau of Mines, in its studies concerned with the retorting of oil shales,[10] found that

> As the temperature is raised, the organic matter of the shale decomposes and produces vapors which condense to form shale oil. Simultaneously, fixed gases are evolved. When the organic matter of a typical shale is heated, it changes first to a soluble bitumen and, as the heating continues, this bituminous substance further breaks down or 'cracks' and forms shale oil. . . . Although most shales apparently begin to give off vapors at 300° to 375°C., these same shales will slowly decompose and yield oil at temperatures as low as 100° to 200° C. To retort the shales completely at such low temperatures, however, would require many hundreds of years.

It was further demonstrated that

> . . . identical methods of retorting give different oils from different oil shales and also that the same shale yields markedly different oils when the conditions of retorting are changed.

The oil produced at the lower retorting temperatures was found to be of better quality and to contain a larger proportion of saturated hydrocarbons than that obtained at higher temperatures. Analysis of the shale gas showed that it was composed of nitrogen, hydrogen, hydrogen sulphide, carbon monoxide, carbon dioxide, ethane, methane, and unsaturated hydrocarbons.

Microscopic examination of various "source rocks" during the course of heating[11] has shown that the visible organic constituents, and in some cases their separate parts, undergo marked changes in appearance as the temperature is raised. These are first noted at temperatures varying from 115° to 150° C. When heating is conducted in an atmosphere of inert gas, the effects observed, such as changes in color and volume, softening, fusion, loss of volatile matter and carbonization of the residue, and the temperature at which these changes take place, that of the melting point in particular, are characteristic of a given type of material in a given shale. The reactions are materially altered by the presence of even small amounts of oxygen and further differences are noted when the rate of heating is changed. Somewhat greater alterations were observed in some materials at the same temperature when heated for longer periods of time under high pressures. The distinctive reactions of the separate components are concluded to indicate differences in their chemical composition.

[10] *U. S. Bur. Mines Bull. 210* (1924) and *Bull. 249* (1926).

[11] Taisia Stadnichenko, *op. cit.*

The view widely held by oil shale engineers, in particular, that the oil distilled from "mother rocks" is produced from some more or less definite chemical commodity termed "kerogen" is obviously unsupported.

EFFECTS OF HEAT ON COLORADO OIL SHALE

METHODS OF TESTING

The amount of soluble "bitumen" formed by the action of heat on the insoluble organic matter of oil shales has been shown, both in the experience of previous investigators and in preliminary work on this project, to vary according to the conditions under which the tests were made. Experiments during the past year have been conducted in groups so arranged as to permit separate measurement of factors thought capable of influencing the process of conversion.

Shale samples were prepared for testing by grinding them in a hand mortar to pass a screen of 20 mesh; they were then thoroughly mixed and separated into equal parts according to the number of experiments in the group. A composite sample made up from these parts was reserved for determination of the moisture and soluble organic content of the unheated material.

Heating of the samples was conducted in glass or steel bombs which, unless otherwise noted in specific descriptions, were compactly filled with pulverized shale and substantially evacuated of air by means of a motor-driven vacuum pump warranted by its maker to produce a final pressure less than 0.001 millimeter of mercury. Each bomb was pumped continuously for one hour; it was then sealed without rupture of connections and before the pump was stopped. Glass bombs made from heavy test tubes furnished satisfactory containers for use at the lower temperatures and could be easily sealed by fusion of their delivery tubes. They were found to be impractical at temperatures over 250°C. since the pressure of accumulated gases often caused them to burst with explosive violence. Steel bombs were developed for use at the higher temperatures, of a design that permitted their repeated use as well as the withdrawal for measurement of gases evolved during the course of heating. At the lower temperatures the bombs were heated in carefully regulated electric ovens; temperatures above 250°C. were obtained in an electric muffle furnace.

Changes produced in the character of the organic matter in the various tests were gauged in all cases by comparing the amount of chloroform-soluble "bitumen" extractable from the heated samples with the amount that could be obtained from an unheated sample of the same material. Determinations of "bitumen" content were made

TABLE I

Hours Heated	Grams Shale in Tube	Volume of Gas at Atmos. Press.	Per Cent Drying Loss	Per Cent Extract	Per Cent Change
		UNTREATED SHALE			
...	...	...	0.26	3.120	...
		SHALE HEATED IN SEALED TUBES IN VACUUM AT 150°C.			
3	30.41	...	0.23	3.106	−0.4
6	39.20	...	0.295	3.127	+0.2
12	30.73	+0.1 cc.	0.275	3.090	−0.9
24	30.44	−5.9	0.27	3.031	−2.8
48	30.45	...	0.22	2.929	−6.1
96	31.20	...	0.22	2.959	−5.2
192	30.95	−0.3	0.17	2.974	−4.7
288	30.11	0.0	0.205	3.060	−1.9
384	30.05	...	0.16	2.896	−7.1
480	33.13	−2.5	0.165	3.041	−2.5
612	32.42	+0.4	0.155	2.536	−18.7
780	38.45	0.0	0.17	2.760	−11.5
		SHALE HEATED IN SEALED TUBES CONTAINING AIR AT 150°C.			
3	40.13	...	0.29	3.140	+0.6
6	37.99	−1.5 cc.	0.25	3.100	−0.6
12	30.36	−1.2	0.31	3.105	−0.5
24	31.56	−0.4	0.285	3.066	−1.7
48	31.10	−0.8	0.265	3.071	−1.5
96	28.50	+0.3	0.245	3.145	+0.8
192	31.50	−0.3	0.22	3.079	−1.3
288	30.88	...	0.251	3.153	+1.1
384	29.66	−0.6	0.251	3.156	+1.1
480	39.89	−0.1	0.265	3.230	+3.5
612	33.56	...	0.245	3.200	+2.5
780	36.72	+2.0	0.235	3.346	+7.2

TABLE II

Hours Heated	Grams Shale in Tube	Volume of Gas at Atmos. Press.	Per Cent Drying Loss	Per Cent Extract	Per Cent Change
		UNTREATED SHALE			
...	...	...	0.165	2.89	...
		SHALE HEATED IN VACUUM IN BOMBS AT 250°C.			
3	27.4	−1.6	0.16	3.12	+7.9
6	28.1	...	0.145	3.11	+7.6
12	27.7	...	0.14	3.11	+7.6
18	30.2	−1.2	0.16	3.10	+7.2
24	30.2	−1.7	0.12	3.10	+7.2
36	28.2	−0.9	0.13	3.11	+7.6
48	29.6	−0.4	0.14	3.12	+7.9
60	29.8	+0.5	0.11	3.15	+8.9
72	28.6	+0.7	0.065	3.01	+4.1
96	30.2	+0.9	0.10	3.27	+13.1
120	28.6	+1.1	0.08	3.36	+16.9
144	28.8	+3.9	0.145	3.47	+20.1

TABLE III

Hours Heated	*Per Cent Drying Loss*	*Per Cent Extract*	*Per Cent Change From Yield of Untreated Sample*
	UNTREATED SHALE		
...	0.18	2.88	...
	SHALE HEATED IN VACUUM IN BOMBS AT 300°C.		
½	0.06	2.93	+1.7
1	0.125	3.11	+8.0
2	0.14	3.14	+9.0
4	0.155	3.27	+13.5
6	0.11	3.34	+16.0
9	0.08	3.34	+16.0
12	0.09	3.68	+27.7
18	0.005	3.45	+19.7
24	0.135	4.13	+43.4
36	0.125	4.26	+47.9
48	0.025	4.21	+46.1
60	0.14	4.81	+67.0
72	0.145	5.03	+74.6

TABLE IV

Hours Heated	*Grams Shale*	*Volume of Gas at Atmos. Press.*	*Per Cent Drying Loss*	*Per Cent Extract*	*Per Cent Change from Yield of Untreated Sample*
		UNTREATED SHALE			
...	...	...	0.195	3.07	...
		SHALE HEATED IN VACUUM IN BOMBS AT 350°C.			
½	86.8	...	0.11	3.51	+14.3
1	87.1	132	0.12	4.12	34.2
1½	92.0	82	0.18	4.74	54.4
2	92.9	161	0.24	6.06	97.4
2½	86.4	162	0.185	5.22	69.9
3	85.8	93	0.195	6.29	104.0
3½	89.2	159	0.24	7.13	132.2
4	86.2	281+	0.29	8.24	169.4
6	88.6	90+	0.215	8.23	168.0
8	88.9	211	0.41	10.81	252.1
10	91.6	240	0.455	11.12	262.2
12	93.9	360+	0.485	12.42	304.5
16	91.2	102	0.365	12.26	299.3
20	90.0	282	0.57	14.28	365.1
24	88.7	414	0.69	15.85	416.2
30	90.7	435+	0.80	16.64	442.0

uniformly according to the method described by J. E. Hawley[12] in a previous report on this project. The procedure is as follows.

Preparation of shale.—The shale is ground in air in a porcelain or steel mortar, fine enough to pass an 80-mesh standard Tyler screen. A quarter of the sample is then weighed in a glass weighing bottle and dried in a nitrogen atmosphere in an electrically regulated oven at 105° C. A 5–6 hour drying period is sufficient to eliminate the moisture without an undue loss of volatile hydrocarbons. After cooling in a nitrogen atmosphere the sample is weighed and the moisture content determined.

Extraction of shale.—The remainder of the sample, which is not dried, is extracted with chloroform for a period of 24 hours, in a Soxhlet extraction apparatus, using fat-free paper thimbles and electric hot plates, at a low heat. The solution of chloroform and organic matter is then distilled down, the chloroform recovered, and the concentrated organic matter transferred to a weighing bottle. The remainder of the solvent is then evaporated slowly at 35° C. (in 24 hours or more), and finally the sample is dried in a current of nitrogen for 2 hours at 50° C. This eliminates the last trace of chloroform.

TYPES OF EXPERIMENTS

Quantitative determinations of the amount of soluble "bitumen" formed from the organic matter in Colorado shale during various periods of time at temperatures of 150°, 250°, 300°, and 350°C., and under otherwise similar conditions, were made for the purpose of obtaining comparative data for further tests with the same material. The results obtained are shown in Tables I to IV.

In tests made at 150°C., individual samples were heated in sealed glass bombs for periods of time varying from 3 hours to more than 32

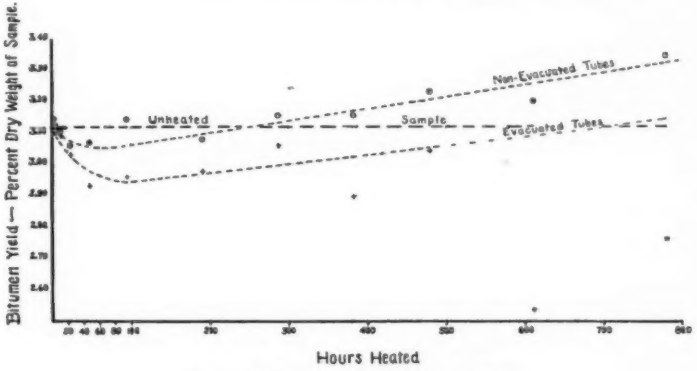

FIG. 1.—Bitumen formation at 150° C.

[12] J. E. Hawley, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 4 (April, 1929), p. 326.

days. Pore space in the tubes was minimized by filling them as compactly as possible. The tubes were divided into two groups. Each tube in one of the groups was attached to the vacuum pump for a period

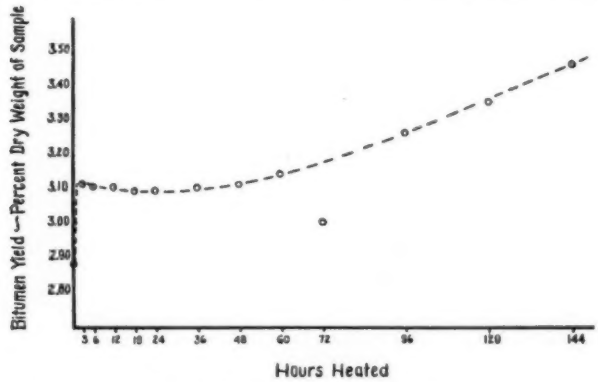

FIG. 2.—Bitumen formation at 250° C.

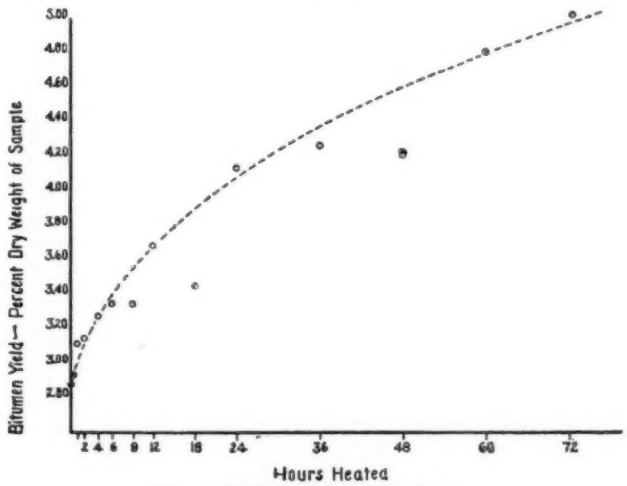

FIG. 3.—Bitumen formation at 300° C.

of one hour and was then sealed before removal by fusion of a previously constricted portion at one end. Tubes in the second set were sealed without evacuation of air. Both groups were heated in a thermostatically controlled oven and for the same lengths of time.

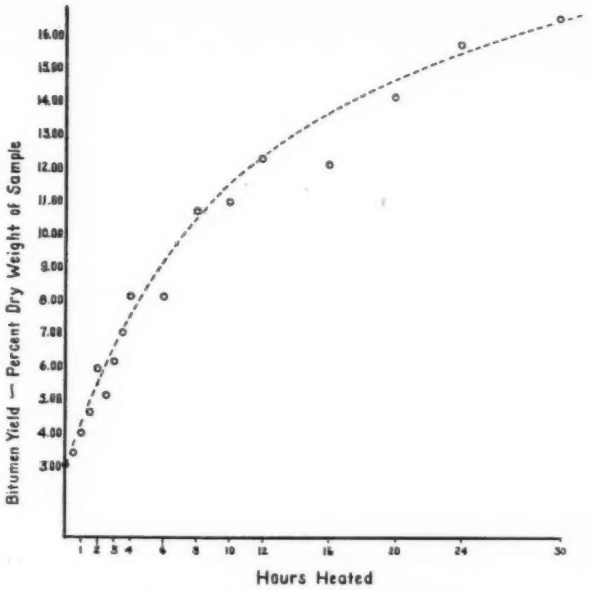

FIG. 4.—Bitumen formation at 350° C.

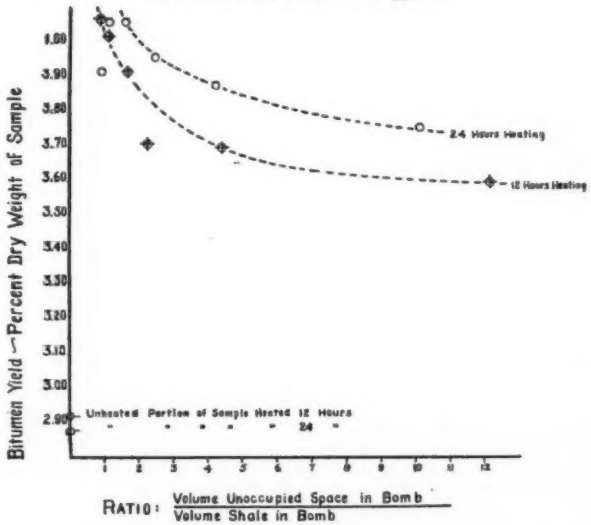

FIG. 5.—Effect of void space on bitumen formation.

Samples heated at temperatures of 250°, 300°, and 350°C. were enclosed in steel bombs. All samples were compacted as tightly as possible by jarring the bombs until no more material could be introduced. All, likewise, were evacuated of air before the bombs were sealed. Tests at 250°C. were heated in an electric oven for periods of time up to 144 hours. Samples were heated during intervals up to 72 hours at 300°C. and to 30 hours at 350°C. in an electric muffle furnace having a temperature variation of approximately ±5°.

TABLE V

Grams Shale in Bomb	*Volume of Shale, Cc.*	*Volume of Free Space in Bomb*	*Ratio: Vol. Free Space to Vol. Shale*	*Per Cent Drying Loss*	*Per Cent Extract*	*Per Cent Change from Yield of Unheated*
			UNTREATED SAMPLE			
....	....	....	....	0.155	2.92	....
			SHALE HEATED IN VACUUM IN BOMB FOR 12 HOURS AT 300°C.			
84.8	42.8	38.6	0.90	0.145	4.07	+39.4
77.3	39.0	45.3	1.16	0.09	4.02	37.6
59.9	30.2	51.3	1.70	0.12	3.92	34.2
49.9	25.2	57.3	2.28	0.095	3.71	27.0
30.0	15.1	66.9	4.43	0.11	3.70	26.7
14.9	7.5	79.6	12.19	0.125	3.60	23.2
			UNTREATED SAMPLE			
....	....	....	....	0.15	2.88	....
			SHALE HEATED IN VACUUM IN BOMB FOR 24 HOURS AT 300°C.			
81.1	41.0	40.4	0.96	0.18	3.92	+36.1
74.9	37.8	44.1	1.17	0.145	4.06	41.0
60.0	30.3	48.8	1.61	0.175	4.06	41.0
45.1	22.8	51.3	2.50	0.19	3.96	37.5
30.0	15.1	64.5	4.26	0.175	3.88	34.7
15.0	7.6	77.2	10.11	0.155	3.76	30.6

Another series of tests was made for the purpose of determining the extent to which the comparative volume of open space about the shale affects the amount of bitumen formed during the course of heating. The variable factor in each test was the ratio between the volume of the shale sample and the volume of unoccupied space in the bomb. A geological counterpart of these conditions is seen in the presence of porous formations of varying capacity lying in contact with possible "source rocks." Differences in the volumetric ratios within the bombs were established by varying the amounts of material charged into them. When packed as tightly as possible, the bombs contained approximately 85 grams of powdered shale. The charges were varied from about 15 grams to the full capacity of the bomb;

their volume was determined on the basis of their weight and specific gravity. The effect of time as a variable factor under these conditions was studied by varying the heating period of groups of samples having similar ratios of volume. The results of these tests are shown in Table V.

A third series of tests was conducted for the purpose of determining the influence of hydrocarbon gases on the formation of "bitumen." The results, shown in Table VI, are inconclusive. Bombs containing

TABLE VI

Grams Shale	*Gas Conditions in Bomb*	*Vol. Gas in Cc. at Atmos. Press. After Cooling to Room Temperature*	*Per Cent Drying Loss*	*Per Cent Extract*	*Per Cent Change from Yield of Unheated*
		UNTREATED SAMPLE			
....	....	.....	0.19	3.00	....
		SHALE HEATED IN SHALE GAS IN BOMB FOR 24 HOURS AT 300°C.			
74.8	Vacuum	48.2	0.125	3.98	+32.7
88.7	Shale gas at atmos. press.	28.1	0.125	4.18	39.3
83.5	Shale gas at 20 lb. press.	−7.8	0.12	3.94	31.3
85.8	Shale gas at 40 lb. press.	11.3	0.14	4.21	40.3
83.7	Shale gas at 60 lb. press.	107.6	0.145	4.19	39.7
109.6	Shale gas at 75 lb. press.	....	0.15	3.80	26.7

samples of the shale were tightly filled as before and, as completely as possible, evacuated of air. The space previously occupied by the air was then filled at different pressures by a combustible gas produced by heating a large sample of the same shale in a closed retort. This was accomplished mechanically by collecting the gas over water and then forcing it into the bombs with the aid of a pressure pump.

Carbon analyses of a selected group of specimens were made by R. J. McCubbin, chemistry department, University of Wisconsin, for the purpose of obtaining information as to the amount of organic material volatilized during heating under various conditions. The samples were chosen from three groups: (1) a set of samples from the Government Mine, Colorado, which had been heated at 150°C. in a nitrogen atmosphere and at atmospheric pressure for various periods of time, (2) the group in which bombs were charged with varying amounts of shale and heated for 12 hours at 300°C., and (3) the set of specimens heated in tightly filled bombs for different lengths of time at 350°C. The results are shown in Table VII.

TABLE VII

SHOWING EFFECTS OF TREATMENT ON TOTAL CARBON CONTENT[1]

Volume of Shale in Bomb	*Volume of Free Space in Bomb*	*Per Cent Drying Loss*	*Per Cent Extract*	*Total Per Cent Carbon*
		UNTREATED SAMPLE		
....	....	0.155	2.92	20.89
SAMPLES FROM GOVERNMENT MINE, RULISON, COLORADO, HEATED IN VACUUM IN PARTIALLY FILLED BOMBS FOR 12 HOURS AT 300°C. SEE TABLE V.				
39.0	45.3	0.09	4.02	21.5
30.2	51.3	0.12	3.92	20.92
15.1	66.9	0.11	3.70	20.95
7.5	79.7	0.125	3.60	21.31

Hours Heated	*Per Cent Drying Loss*	*Per Cent Extract*	*Total Per Cent Carbon*
	UNTREATED SAMPLE		
....	0.55	3.96	24.03
SAMPLES FROM GOVERNMENT MINE, NEAR RIFLE, COLORADO, HEATED IN NITROGEN AT ATMOSPHERIC PRESSURE AT 150°C.			
6	0.305	3.60	23.64
24	0.30	3.25	23.06
96	0.14	3.05	23.82
	UNTREATED SAMPLE		
....	0.195	3.07	18.39
SHALE FROM GOVERNMENT MINE, RULISON, COLORADO, HEATED IN VACUUM IN BOMBS AT 350°C. SEE TABLE IV.			
2	0.24	6.06	18.4
2½	0.185	5.22	18.71
4	0.29	8.24	18.05
8	0.41	10.81	17.92
12	0.485	12.42	17.49
30	0.80	16.64	17.43

[1] Chemical analyses made by R. J. McCubbin, chemistry department, University of Wisconsin.

DISCUSSION OF RESULTS

Several of the samples heated in vacuum at 150°C. showed low and irregular yields of "bitumen." The drying losses in these cases were conspicuously smaller than in their companion samples that were heated for the same length of time. It is believed that slight cracks may have developed in the tubes during the course of heating that allowed the escape of some volatile materials. While the differences in yield of "bitumen" from most of the samples are so small that they would ordinarily be considered as falling within the limits of experimental error, certain trends in their behavior are in evidence when the results are plotted. Both in the evacuated and in the non-evacuated tubes, heating produced initial losses in the yield of soluble "bitu-

mens" during the first few hours. These losses were followed, especially in the case of those samples heated in the presence of some air, by yields which increased in amount according to the length of the heating period. Samples from the evacuated tubes showed slightly lower yields than did those from the tubes containing air. Only small amounts of gas were generated, even in those tubes heated for 30 days. In many cases the quantity formed was insufficient to restore atmospheric pressure within the bombs; in a few cases sufficient gas was formed to create very slight pressures.

The rate of "bitumen" formation is noticeably increased at 250° C. and becomes much more rapid at 300° C. Approximately 9 per cent more "bitumen" was extractable from shale heated for 60 hours at 250° C. and approximately 67 per cent more from that heated for the same length of time at 300° C. than was recoverable from unheated samples of the same material. These differences correspond respectively to 0.26 per cent and 1.93 per cent of the total dry weight of the shale sample and, obviously, to much larger percentages of the weight of the organic matter in the shale.

Shale samples heated at a temperature of 350° C., and under otherwise similar conditions, show large amounts of insoluble organic matter converted to a soluble form in short periods of time. Approximately 3 per cent of the dry weight of the unheated shale was extractable as chloroform-soluble "bitumen," whereas 16.6 per cent of the dry weight of the sample was recovered as extract from shale heated for 30 hours at a temperature of 350° C. The speed of reaction appears to decline as the period of heating is extended. Large quantities of gas are formed at this temperature with the consequent result that conconsiderable pressures develop within the bombs.

The problem of keeping the bombs hermetically sealed during the period of heating and subsequent cooling becomes increasingly difficult as the temperature is raised. At temperatures below 300° C., comparatively small amounts of gas are evolved and, in most cases, only slight pressures are found in the bombs when they are opened after cooling. Leakage of volatile matter during the course of heating can scarcely be detected, therefore, until the final analyses for the entire group are completed, when its occurrence is denoted by unusually low drying losses accompanied by correspondingly low "bitumen" yields in the samples affected. Surprisingly regular curves are obtained when "bitumen" yields are plotted according to the time during which the samples were heated. Analyses whose positions fall distinctly short of the regular trend are almost invariably those obtained from samples taken from bombs showing no gas pressure.

No change in the physical appearance of samples heated at temperatures of 150° and 250° C. can be discerned by the unaided eye, and only slight changes are apparent at 300° C. Enough change is produced at 350° C., however, to permit an easy arrangement of samples according to the length of time that they were heated, both from their appearance and from their odor. The crushed, unheated material is of a light gray color. This becomes somewhat darker after several hours of heating at 300° C. The gases accompanying the heated material contain hydrogen sulphide, but when they have been released the shale itself has a faintly pungent and somewhat aromatic smell. Samples heated for long periods show a slight tendency toward coherence after cooling in the bombs, which suggests the possibility that the organic matter softened sufficiently to form a weak binder. These effects are much more apparent in material heated at 350° C. The material then becomes rapidly darker in color as the time of heating is extended; its shade is of a deep, brownish black after heating for a period of 30 hours. Softening takes place to an extent sufficient to cause the shale to adhere to the sides of the bomb and to form a well compacted and lightly coherent mass. In addition, the shale has the feeling and appearance of having been moistened, although no separate drops of liquid were observed on opening the bombs. The moist condition soon passes unless the sample is tightly stoppered. It probably indicates the presence of liquid hydrocarbons that are easily volatilized at room temperatures and atmospheric pressure. The odor of the shale also increases with the time of heating but is not at all unpleasant.

The results of tests made for the purpose of determinining the influence of free space about the material on the formation of soluble "bitumen," although showing inconsistencies due to leakage of gas from certain bombs, indicate that the amount of "bitumen" formed under any set of conditions and during a definite period of time depends to a measurable degree upon the relative volume of space to which the gases evolved have access. The handicap of this variable consistently retards the amount of conversion effected by time.

Samples heated in the presence of shale gas introduced in replacement of air show indeterminate results. Three of the samples tested yielded slightly larger amounts of "bitumen" and two of them slightly smaller amounts than did a companion sample heated in a vacuum, although the latter itself yielded somewhat less than did similar samples heated under similar conditions in other groups of tests. While the gases introduced were derived from the organic matter of the same shale, they were formed under conditions of pressure and

temperature different from those later present within the bombs. Their failure to affect the formation of "bitumen" may have been due to their chemical difference from the gases normally produced in testing.

Curves showing the amount of "bitumen" produced during various intervals of time may be plotted from the results obtained at the temperatures employed. The slope of such curves pictures the rate of conversion. At temperatures of 150° and of 250° C., the trend of the curves obtained was concave upward, showing that the maximum rate of conversion was not achieved during the time that the samples were heated. Near the beginning of the heating period, initial gains in "bitumen" yield were followed in each case by slight declines and then, later, by regular increases. This reduction in yield was less at the higher temperature. At temperatures of 300° and 350° C., the curves obtained were convex upward and, excepting for differences in slope, quite similar in shape. No break in the initial rate of yield was shown. The shape of the curves shows that the time of heating was more than sufficient to produce the maximum rate of conversion at these temperatures. Decomposition of "bitumen" already present in the shale is believed to have caused the initially decreased yields in samples heated at the lower temperatures. Formation of new "bitumen" at a rate exceeding that at which the material is volatilized apparently begins when the vapor pressure of the gases evolved reaches a critical point for the temperature maintained. In so far as increases in temperature speed up the reactions involved, conditions favoring the formation of "bitumen" are the more quickly attained.

Percentage weights of carbon in shale samples were determined according to the methods of combustion analysis. It is to be noted that the mineral matter of the shale contains both carbonates and sulphides, neither of which could be separated from a sample without loss of volatile constituents from the organic matter. At temperatures reached in the combustion furnace, these minerals give up carbon dioxide and sulphur dioxide, which are both absorbed with the carbon dioxide produced by combustion of organic matter and are measured as having been derived from the latter source. The results shown are, therefore, in error, according to the amounts of material contributed by the unavoidable reactions. They may, however, be compared within their own groups, provided there is evidence that similar amounts of inorganic material were absorbed from each sample. The argument is indefensible, but this assumption is held so long as variations are consistent in the results obtained.

Samples of shale that had been heated in partially filled bombs showed differences in their percentage weights of carbon that can not

be related to the conditions set up in the tests. Differences in the mineralogical composition of the samples is assumed to have caused the apparent confusion. With one exception, the carbon content of samples heated in nitrogen and at atmospheric pressure was found to decline as the period of heating had been extended. The same effect was found with smaller losses, but with more regularity, in samples that had been heated in tightly filled bombs at 350° C. where volatilization had taken place under increasing gas and vapor pressures. Volatilization of organic material in laboratory tests apparently occured under all conditions and during the entire time of heating at temperatures exceeding 100° C.

The volumes of gas generated from the shale during heating were measured when possible. No considerable amounts were found except in the tests made at 350° C. and no relation can be observed between the amount of gas evolved and the amount of "bitumen" produced beyond the fact that tests in which leakage of gas occurred showed erratically decreased yields of extract. This, in itself, is significant, since it indicates that the maximum amount of "bitumen" is formed at a given temperature only when sufficient vapor pressures are maintained to restrict volatilization.

SUMMARY

Experimental data on hand substantiate the conclusion previously expressed by the Bureau of Mines that changes produced in the character of fossil organic matter as a result of heating are due to fractional decomposition of its chemically complex structures. When such material is heated in the open air, the end products of the reactions induced appear to be volatile gases and fixed carbon. When heating is conducted in a closed vessel, various intermediate products are formed. None of these has been chemically identified in this work; their presence has been recognized by changes in the color and appearance of the shale, by increased percentages of soluble organic matter, and when heating has been sufficient, by the moistened condition of the treated sample.

The nature of the intermediate products is believed to depend in part on the type and state of preservation of the organic material in the shale. Different rocks, when subjected to the same heat treatment, yield extracts of soluble organic matter which differ in color, odor, and dried appearance. The differences in character of the soluble products obtained from a given shale under various conditions of heating are not so readily apparent; variable results are more easily noted

in the amount of "conversion" effected and in the volume of gases produced.

Changes experimentally produced in the fossil material during the course of this work were measured by comparing the amount of chloroform-soluble "bitumen" that could be extracted from unheated shale with the amounts obtainable after samples were heated. The results obtained were uniformly determined, but in so far as they represent the total of effects produced, they are obviously qualitative. However, this method appears to be the only practical means of estimating the effects produced by heating at low temperatures and during laboratory intervals of time.

The formation of soluble "bitumens" under thermal conditions is affected in laboratory experiments by three variable factors and the results produced represent the net effect of their simultaneous operation. These variables are temperatures, time, and the volumetric ratio between the organic matter in the rock and the pore space accessible to gas.

The rate of "bitumen" formation depends, under otherwise favorable circumstances, on the temperature at which the shale is heated. For a specific interval of time, this rate is further influenced by the amount of "bitumen" previously formed. The minimum temperature at which this product forms is not known. Experiments show that Colorado shale is readily devolatilized at 105° C. and that small amounts of "bitumen" are formed in closed tubes at 150° C. when heating is continuous for two or three weeks. So far as the process has been carried in the laboratory, the rate of conversion increases as temperatures are raised. During the first 24 hours of heating, approximately 6 times as much "bitumen" was formed at 300° and 61 times as much as 350° as was formed in the same time at 250° C.

The factor of time is of varying importance. In laboratory tests it determines in part the amount of "bitumen" formed at a given temperature, but its relative influence depends on the rate of conversion. Its maximum effect is found at high temperatures and during the early part of the conversion process. At temperatures below 150° C., its effects are so slight as to be measured with difficulty and there is some basis for a reasonable doubt that large amounts of "bitumen" are formed at these temperatures during even geologic time.

The volumetric ratio between organic matter and adjacent pore space determines the extent to which volatilization proceeds, especially at low temperatures, before "bitumen" formation begins. Vapor pressures sufficient to retard volatilization at the temperatures employed are undoubtedly necessary to "bitumen" formation.

A broad view of the foregoing experimental results strongly suggests that the organic products formed from oil shales and kindred rocks as a result of heating are derived from their insoluble organic constituents as a result of a cracking process. It is believed that some of the cracked products may be immediately soluble and others immediately volatile. On the other hand, certain constituents are undoubtedly broken up more than once before they are reduced to the state of hydrocarbon gases or to the materials herein called "bitumen." The physical conditions attending the reaction apparently determine the amount of conversion and the nature of the products formed, but it is to be noted that in the absence of especially favorable conditions the trend is toward the production of volatile gases and fixed carbon.

SUGGESTIONS

There remain several unfinished and important phases of the investigation already begun. While considerable information has been obtained and a few generalizations have been tentatively drawn, the evidence is incomplete and therefore subject to controversial interpretation. Especially is this true in that part of the work concerning the extent to which the element of time can augment the effects produced by low temperatures. The following comments and suggestions are made, not in criticism of previous and essential work, but to point the directions in which information is lacking.

From the fact that soluble products have been observed to form at all temperatures in the range from 150° to 350° C., and that the amount formed can be somewhat increased in each case by extending the length of the heating period, it has been commonly assumed but not proved that, given sufficient time, the effects produced at high temperatures might be duplicated under the same conditions at much lower temperatures, and, possibly, even in oil-bearing strata in nature. Except that they are hydrocarbons, soluble in organic solvents and solid or semi-solid at ordinary temperatures, the chemical nature of these "bitumens" is so far unknown. A variety of products could satisfy these conditions. The widely different rates at which this soluble material forms in Colorado shale within a temperature range of 50° above and below 300° C. creates the double suspicion that the "bitumen" does include a variety of products and that these products may be formed from the various organic ingredients of the shale at different temperatures. The idea is further sustained by the microthermal observations previously referred to. While the time involved makes such work impracticable at temperatures below 250° C., valu-

able information could be obtained if the absolute limits of conversion were determined at various temperatures above that point. A correlative study is the organic analysis of the soluble products formed at different temperatures.

It has also been assumed that, since the bitumen formed at high temperatures decomposes to oil (or to vapors which condense to oil at ordinary temperatures), the "bitumen" formed at the lower temperatures will undergo the same process, given sufficient time. To the writer's knowledge, this has not been proved and the possibility should be checked by long-time tests at temperatures of 250°–300° C.

Complete conversion of the insoluble organic matter in the shale, even to the form of "soluble bitumen," appears improbable under either natural or artificial conditions, by process of thermal decomposition alone. Under geological conditions, especially, volatilization of material is certain to occur so long as temperatures are sufficient to produce it and opportunity exists for escape of gases into the pore space of the mother rock or of the rocks adjoining it. So far as this process results in a disproportionate loss of hydrogen, there is, undoubtedly, carbonization of the remainder and a trend toward permanent insolubility. After considering again the visible effects of heat on the various organic ingredients, it is seen that tests are needed to determine the maximum loss of material by volatilization at different temperatures and the degree of carbonization resulting.

The work of Project No. 1 has been devoted principally to a study of the effects of shearing pressure and of heat on the organic matter of oil shales. Much work has been done on this phase of the metamorphism of organic materials both previously and contemporaneously, but the labor is far from complete. F. H. Lahee has outlined some of the dependent and related problems whose solution might be profitably attempted by subsequent investigators. With the hope that they may stimulate further research, he has kindly suggested[13] that the following studies may assist in discovering the mechanics of petroleum formation.

1. The problem of *load* pressures, as distinguished from *shearing* pressures, should be investigated. Before we can go far in theories of oil generation and oil migration, we must learn more about the effects of burial and loading on the compaction of sediments and on their original fluid contents. . . .

2. An investigation of the stratigraphy and topography should be made in the regions of the present oil pools to learn anything possible concerning the probable maximum depth of burial of the oil sands before and after accumulation of petroleum in the reservoir, and the relations of the time of fold-

[13] F. H. Lahee; letter written, January 6, 1931.

ing to these factors. This would be for the purpose of finding out to what approximate temperatures the sands had been subjected. It would require a knowledge of paleogeographic history.

3. It is possible that an extended study might be made of the relations of "rock pressures" in oil and gas pools to hydrostatic pressure at the depths of the producing sands. A considerable literature exists on this subject, but I think there is room for a special, comprehensive study, involving a compilation of data. This is indirectly related to some of the other factors mentioned above.

4. Another problem concerns the time at which the volatile substances begin to come off from the organic matter, and the time, in the sequence of sedimentation, when these gases begin to suffer retention. This, it seems to me, is closely related to the problems of compaction.

5. In investigations similar to Project 1, whenever any such are contemplated, I would suggest the collection and use of samples of "source material" from the areas where Dr. Trask found muds peculiarly suitable for source rocks of oil.

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CONVERSION OF FATTY AND WAXY SUBSTANCES INTO PETROLEUM HYDROCARBONS[1]

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ABSTRACT

The most stable portions of organic tissues are fatty acids. It is assumed petroleum is formed from a wax-like substance. When a pure hydrocarbon is heated in a bomb a complex liquid and gaseous mixture is obtained. The reverse does not occur. Hydrocarbons are known to be unstable at high temperatures and investigation has shown that the rate of decomposition in either the gaseous or liquid phase follows the monomolecular law. Thus there is no definite temperature at which reaction begins and the rate of decomposition at any temperature can be calculated by the Arrhenius equation. Experiments have shown that when saturated hydrocarbons are heated, unsaturated hydrocarbons are produced and that a fraction of them undergo molecular rearrangements to form saturated cyclic hydrocarbons. A further fraction polymerizes or recombines to form complex hydrocarbons of the branched chain or ring type. The transformation of the waxy substances can then be regarded as a sort of low-temperature, high-pressure distillation process in which pressure favors the production of cyclic hydrocarbon. Ultimately, only gases, composed of low molecular weight hydrocarbons, and a dense semi-solid or asphaltic material remain. The maximum depth of oil wells should not greatly exceed 20,000 feet.

INTRODUCTION

It has frequently been pointed out by chemists that the fatty acids are the most stable organic substances of animal tissues. The proteins and carbohydrates are quickly acted upon by bacteria of various kinds and are decomposed into simple substances readily soluble in water. The hydrolysis of fats takes place with equal ease; whereupon the free glycerine and acids of low molecular weight are removed by water. There is thus left behind a semi-solid mass of waxy material which is in time converted into soaps or salts of calcium and magnesium. Such residual substances have been found in damp places and have been given the name adipocere. The wide occurrence of these remains of adipose tissue, in beds whose age can easily be determined, is itself a proof of the stability of the fatty acids.[3]

[1] Manuscript received, June 28, 1932. Revised manuscript received, May 1, 1933.

[2] Associate professor of chemistry, University of British Columbia. Introduced by Theodore A. Link.

[3] *Science News Letter* of March 11, 1932, has an interesting item bearing on this problem. Twenty or thirty years ago a boat load of herring went aground off Admiralty Island near Alaska. In time the boat disappeared and the fish decomposed, leaving on the bottom of the sea a waxy substance. This proved to be a complex compound of several acids formed by the decomposition of the fat in the fish, combined with calcium and magnesium in the sea water.

In the case of plants, besides fatty acids, the residual tissue contains humic acids derived from the lignin of the wood. This apparently becomes the humus of the soil under favorable conditions (1).[4]

The origin of petroleum, according to Brooks and others, should be sought in some type of material such as adipocere. This waxy semi-solid stuff made up of fatty acids and hydrocarbons such as can be synthesized by low forms of life must, in the words of Brooks (2), be regarded as the "proto-petroleum" and not the mixture of saturated and unsaturated compounds obtained by Engler in his classic experiment on fish oils.

The difficulty so far has been to account for the transformation of these fatty and waxy substances into the complicated and saturated hydrocarbons found in petroleum. In the following pages an attempt is made to explain this transformation in the terms of present-day hydrocarbon chemistry.

COMPLICATED NATURE OF PETROLEUM

One of the most outstanding characteristics of petroleums is their complexity. That this should be so need not be surprising in view of the enormous possibility of isomerism in either the paraffine or naphthene series of hydrocarbons. It might at first be supposed that hydrocarbon mixtures differed little from one another in complexity, because of the transitional nature of the rise of the boiling-point when samples of either are subjected to fractional distillation. Experience has shown, and theoretical considerations predict, that such is not the fact. In the first place, it is obvious that the naphthene hydrocarbons with alkyl side chains will not only possess all the isomeric possibilities of the paraffines, but will have position isomers as well, due to the ringed nature of this series. Thus it is possible to have isomers even closer in physical and chemical properties than in the case of the branched chained hydrocarbons of the paraffine series. This accounts for the difficulty met with in trying to obtain fractions which will not crystallize even after 10 or 15 different fractionations. No such difficulty confronts one in working with the paraffine hydrocarbons, in which crystallization takes place merely after removal of the lighter fractions. There can therefore be no doubt that the petroleums containing a large amount of naphthenes represent more complexity than other types. The asphaltic base petroleums must thus be regarded as extreme cases of complexity.

It is a well known fact that if any pure hydrocarbon of the straight chained series, either paraffine or olefine, is heated in the ab-

[4] Numbers in parenthesis refer to bibliography at end of this article.

sence of air, a complex mixture of hydrocarbons is obtained. Experience has shown that such a mixture contains not only saturated and unsaturated hydrocarbons with greater or lesser molecular weights than the original, but also branched and cyclic compounds as well. The reverse does not occur, that is, a pure hydrocarbon is never obtained by merely heating a mixture of hydrocarbons. The thermal decomposition of hydrocarbons is thus an irreversible process. Further, it is possible to produce an asphalt-like material from a paraffine base petroleum by thermal treatment, but a paraffinic base can not be formed in a similar manner from an asphaltic base petroleum. Here also the natural process tends by itself to go from the simple to the complex.

The work of Mabery has shown that the paraffine base petroleums represented the most simple types, although the number of isomers in any one fraction could still be very great (3). The predominating hydrocarbons were of the straight chain type. Kraft has found the same thing to be true for the paraffine hydrocarbons separated from German brown coal (4). The origin of petroleum must therefore be sought in material containing long hydrocarbon chains, because there is no known purely thermal method by means of which they can be produced. The only sources of such long chains are the fats and hydrocarbons which are synthesized by vegetable or animal organisms. We must assume that the ability to store energy or reserve food material in the form of fat or possibly hydrocarbons was characteristic of the most early and primitive forms of life. Indeed, it has been shown by Kramer and Spilker that diatoms are capable of storing an oily substance which can be converted into petroleum-like liquids (5).[5] Thiessen (6), Stadnikoff, and Weisman (7) have pointed out that the remains of certain species of algae contain a considerable amount of both saponifiable and non-saponifiable oil and waxy material. Long chain hydrocarbons have been found to occur in the leaves and bark of many different species of plant. Thus Power (8) reports the occurrence of the hydrocarbon $C_{35}H_{72}$ in leaves of *Eriodictyon californium*, and Hooper and Arnott (9), in leaves and bark of *Oleo europaea*. $C_{31}H_{64}$ occurs in beeswax, brucia seeds of Sumatra, and in the leaves of Kentucky and Virginia tobacco. The last mentioned plants also con-

[5] John M. Macfarlane in his book *Fishes the Source of Petroleum* (The Macmillan Company) shows that in many species of fish the dried body contains more than 40 per cent fat. He further presents data to establish the fact that fish exist in such large numbers that the fat content of their bodies, if converted into petroleum, would yield quantities of the same order as those found in the earth. The extensive remains of the hard parts of fish skeletons testify to the enormous numbers which lived in past geological ages.

tain $C_{27}H_{56}$. According to Etard (10), the leaves of *Bryonia diocia* contain the hydrocarbon $C_{20}H_{42}$. The solid residue of rose oil consists largely of $C_{18}H_{34}$. These and similar straight-chained hydrocarbons have been found by Mabery (3) in Pennsylvania petroleum and by Kraft in the so-called brown coal of Germany.

The fatty acid radicals of all fats constitute the largest source of long-chain molecules known. Investigation has shown that saponification readily takes place by the help of either organic or inorganic agencies with the result that the glycerine and lower fatty acids are dissolved by water and removed from the fatty acids of high molecular weight. These residual acids are themselves quite stable toward bacterial decomposition.

So far the direct conversions of fatty acids into liquids or solid hydrocarbon by bacterial action has not been observed. Thayer (11) recently re-examined this question with a great deal of care, but could detect no hydrocarbon formation other than methane. Analyses of adipocere show that, in the course of time, the fatty acids are neutralized and preserved largely in the form of lime soaps (12). As early as 1865, Warren and Storer showed that the distillation of either fatty acids or their salts in the form of lime soaps yielded petroleum-like products (13). In these experiments and in those carried on by Engler (14) at temperatures near 450° C., much gas was formed consisting of hydrocarbons, carbon dioxide, and some hydrogen. Hurd, in his monograph, *The Pyrolysis of Carbon Compounds* points out that stearic, palmitic, lauric, and myristic acids can be quantitatively changed into ketones in less than 4 hours at temperatures not exceeding 295° C. when heated in closed iron vessels (15). Ketones are almost as stable as the hydrocarbons themselves, but can be converted into hydrocarbons directly by heating under pressure with the simultaneous formation of hydrocarbons, ketones, and carbon monoxide. There is thus much evidence to show that by heat treatment alone fatty and waxy material can be converted into petroleum hydrocarbons.

UNSTABLE NATURE OF ORGANIC COMPOUNDS

There are two objections to Engler's theory regarding the origin of petroleum. The first is the high temperature required to decompose the fatty acids, and the second, the presence of hydrogen and unsaturated hydrocarbons in the gas, and the unsaturated nature of the liquid fractions. These objections can be avoided if the transformation of fatty and waxy substances into petroleum is regarded as a low-temperature, high-pressure cracking process, instead of a high-temperature

distillation process. This idea, while not new, does not appear to have been sufficiently emphasized, possibly owing to the lack of accurate data which have not been available until lately.

An extensive study of the decomposition of paraffine hydrocarbons in gaseous or liquid phase has shown that all decompose according to the monomolecular law and that therefore their rate of decomposition is a function of temperature alone. Applying the present-day conceptions of energy distributions to a system of organic molecules, it follows at once that there must be a certain fraction of molecules of a certain number whose energy content is above a certain minimum, compatible with stability. In present-day terms such molecules are said to be activated, and if the energy of activation is known, it becomes a simple matter to calculate, by means of the equation $N_1 = N_e^{-E/RT}$, the fraction of molecules, N_1, of a certain number of molecules, N, which have energies greater than E at temperature T. The value of E given in various papers varies from 55,000 to 67,000. There seems to be some evidence that the heat of activation is the same for all aliphatic hydrocarbons, and not far from 65,000. Using this value, Table I has been constructed to show the fraction of molecules which are activated at any one temperature. It will be seen that the number of activated molecules at temperatures below 1,000° C. is very small —about one in every gram molecule at 300° C.

TABLE I

Temperature Centigrade	*Fraction Activated* N_1
20	3.5×10^{-60}
100	1.0×10^{-32}
200	6.0×10^{-26}
300	1.4×10^{-21}
500	3.7×10^{-16}
1,000	1.5×10^{-8}

However, it is not so much the number of activated molecules which is of interest, as the rate at which the molecules become activated and decompose at various temperatures. Experiments have demonstrated that besides temperature the molecular weight for any one series of hydrocarbons is an important factor. Burk (16) has shown, recently, that by slightly modifying the expression developed by Polyani and Wigner for unimolecular reaction velocities, it is possible by means of it to calculate tolerably well the velocity constant for any straight chain hydrocarbon. The relative stability of different hydrocarbons at definite temperatures is also brought out by the formula and, according to Burk, butane would decompose twice as fast as propane (17). This is an important part of our theory, as it

shows that given sufficient time any hydrocarbon would decompose to form smaller and smaller gaseous molecules.

A simpler method of calculating the velocity constants is available if the heat of activation and the velocity constant are known at any one temperature. In such cases the integrated form of the Arrhenius equation, $d\ln k/dT = E/RT$, can be utilized. Data for the velocity constants are available from two sources: Waterman and Perquin (18), who determined the rate of cracking of Ragoon wax in an autoclave, and Gault and Hessel (19), who studied, in a very thorough manner, the rate of pyrolysis and nature of the products formed when cyclohexadecane was decomposed at different temperatures. Kiss (20) has calculated the velocity constant from the results of the former and Burk from the latter. For our purposes it is quite immaterial which figure is used, as the Ragoon wax would correspond very closely with the hypothetical protopetroleum and its average molecular weight would be approximately that of hexadecane. Taking the constant calculated by Burk, and converting it to a minute basis, the figure 0.03456 is obtained as the velocity constant at 470° C. Using this value for K, the velocity constant, and 65,000 as the heat of activation, one gets, with the help of the aforementioned equation, the velocity constants at different temperatures and the half life period of material having a composition similar to that of Ragoon wax or hexadecane.

TABLE II

Temperature Centigrade	K	*One Half Life Period*	*Average Life Period*
470	3.54×10^{-2}	20 minutes	28.8 minutes
400	3.55×10^{-4}	1.4 days	2.0 days
350	7.10×10^{-6}	67.7 days	97.48 days
300	7.25×10^{-8}	18.1 years	26.06 years
250	3.07×10^{-10}	4.28×10^{3} years	6.16×10^{3} years
200	4.11×10^{-12}	3.20×10^{8} years	4.70×10^{8} years
150	1.15×10^{-16}	1.15×10^{10} years	1.65×10^{10} years
100	3.58×10^{-21}	3.68×10^{14} years	5.30×10^{14} years

The remarkable stability of hydrocarbons is at once obvious. This is, of course, in the absence of oxygen or other reactive substances such as sulphur. At 100° C. the stability is greater than that of potassium, and at 150° C. it lies between that of thorium and uranium.[6]

[6] This idea may be applied to various types of organic matter. Thus a consideration of the Polyani-Wigner theory $dN/dt = Nve^{-\epsilon/RT}$ leads us to suppose that where v, the highest frequency in the molecule, is small, and when ϵ, the heat of activation above which a bond will rupture, is small, the velocity of decomposition becomes large even at temperatures of 100° C. or less. In the case of complicated molecules we do not know the value of either v or ϵ. We do know, however, that molecules associated with life processes are extremely unstable and sensitive to heat changes. This must be so for organic molecules even in the most primitive form of spore. Any living organism buried

Consider now the fate of some fatty material buried, during some remote geological period, under ever increasing layers of sediment. With subsidence the temperature of the buried mass will begin to rise and, being shut off from air and other agencies, the only change which can take place is that due to heat alone. The change in general will follow along the same lines whether the buried material was originally in the form of hydrocarbons, fatty acids, or soaps. By assuming the validity of the monomolecular law over the temperature given in the table, it is clear the high temperatures required by Engler for decomposition are not necessary in a natural process where time plays an important role. Experiments on thermal decompositions lead to the idea that decomposition does not begin at any one temperature and that its lower temperature limit is only determined by the sensitivity of our measurements (21). Likewise the table shows that any buried waxy material must have been at some time at a temperature of at least 150° C. to allow for its transformation into petroleum within the limits of geological time. Assuming a temperature gradient of 1 degree centigrade for every 32 meters, a temperature of 100° C. would be reached at a depth of 2,560 meters or approximately 8,390 feet; 150° at 4,160 meters or 14,649 feet; and 200° at 5,760 meters or 18,899 feet. Above 200° the rate of decomposition becomes so high that any fatty or waxy material would soon, geologically speaking, be transformed, as will be seen later, into gas and heavy asphalt.

Now, as has been shown, the fatty and waxy material can only be synthesized by vegetable or animal organisms. As this is of a paraffinic nature it is obvious that petroleum containing a high percentage of solid or semi-solid paraffine hydrocarbons must be either a young petroleum or be the remains of some primordial material which in no time of its history has passed through a temperature much exceeding 100°. As has been mentioned before, anyone who has had experience with the decompositions of hydrocarbons knows that any pure aliphatic substance, if heated in a closed vessel free from air, will in time give rise to a great variety of other hydrocarbons. The reverse never occurs.

SATURATED NATURE OF PETROLEUM HYDROCARBONS

The objection to Engler's theory on the ground that his experiments showed both free hydrogen and unsaturated hydrocarbon to

in such a manner that it can no longer get food or air can not rebuild any molecules which are being decomposed through the action of heat. Even at ordinary temperatures, if the heat of activation is low, some molecules must be decomposing due to their high energy content. In the light of this theory it would appear impossible for any spores or other forms of organisms, say bacteria, to live for any great length of time removed from light and air.

have been formed, whereas neither of these substances is associated with natural petroleum, can at present be answered only in a qualitative manner. It is manifest that the velocity of recombination or rearrangements of the primary decomposition products is governed by the velocity of the primary reaction. There is, however, much indirect evidence that the velocity of polymerization and recombination at temperatures below 300° C. is very much faster than that of decomposition for most hydrocarbons. Kiss, in his attempts to calculate gasoline yields in hydrogenation processes, assumes the velocity of polymerization to be instantaneous. The numerous experiments of Ipatiev (22) and others have demonstrated the fact that olefines are readily condensed into higher olefines or napththenes and also that pressure and various catalysts speed the process tremendously. The rôle of catalysts in this phase of the process of transformation must certainly be stressed in the light of such results as those of Brooks (2) and others, who have found unsaturated hydrocarbons to be polymerized even at ordinary temperature when brought into contact with certain clays or other earthy substances.

The velocity of hydrogenation, being of a second or higher order, must also be influenced by pressure and catalytic agents as well as by temperature. This fact should not be overlooked when considering low-temperature cracking.

WORK OF GAULT AND HESSEL ON HEAVY HYDROCARBONS

The exhaustive work of Gault and Hessel gives us for the first time some reliable information on the nature of the decomposition products of the heavier hydrocarbons (19). They have formulated their results at different temperatures in equations, each of which predominates or makes its appearance at some one temperature.

1. At 390° C. hexadecane distilled without decomposition.

2. At 470° saturated and unsaturated gases and liquids were obtained but no hydrogen.

This is illustrated by the following equation.

a. $R_1CH_2CH_2CH_2R_2 \rightarrow R_1CH=CH_2+CH_2R_2$

b. $CH_3(CH_2)_{14}CH_3 \rightarrow CH_3(CH_2)_{12}CH=CH_2+CH_4$

c. $CH_3(CH_2)_{14}CH_3 \rightarrow CH_3(CH_2)_{12}CH_3+C_2H_4$

3. At 540° the additional reaction made its appearance, yielding free hydrogen.

d. $R_1CH_2CH_2CH_2R_2 \rightarrow R_1CH=CH_2+CH_2=CHR_2+H_2$

4. At 685° a considerable amount of hydrogen was produced as well as aromatic compounds. The origin of the aromatics may be explained in two ways. Most of the evidence available points to equation (e) as being the cor-

rect one, although some of the benzene may possibly have been formed according to the scheme first mooted by Berthelot as in (f).

e. Olefine→cyclohexane→cyclohexene→cyclohexadiene→benzene

f. Acetylene→benzene.

Other reactions beside those mentioned probably also take place, as Paneth and his co-workers claim to have shown the existence of the free ethyl and methyl radicle when hydrocarbons are heated to high temperatures.

PETROLEUM HYDROCARBONS UNDERGO SUCCESSIVE DECOMPOSITIONS AND RECOMBINATIONS

As has been mentioned before, according to the theory of monomolecular reactions, all the foregoing reactions must take place to some extent at any one temperature. The relative amounts of decomposition for the various possible reactions would be some function of the heats of activation and the physical-chemical properties of the compound, and they would also probably be some function of the absolute temperature at which they can first be detected. We should, therefore, on the basis of the theory, expect to find, at say 200° C., at any instant, in a mixture of hydrocarbon material, some olefines and a much smaller amount of hydrogen. Gault and Hessel found at 470° that even in the short space of time during which the hexadecane and hexadecene had been in the tube a certain amount of cyclization had taken place into naphthenes. Thus cyclohexane may be formed either directly from hexylene or by the polymerization of ethylene. Similar reasoning will show that di- or tri-cyclic compounds can be formed from the higher di- or tri-olefines. There are thus three factors at work to reduce the amount of unsaturation of the petroleum hydrocarbons; the rearrangement of unsaturated compounds into rings, the combination of two or more to form rings or larger molecules with a lower hydrogen-carbon saturation ratio and the direct addition of hydrogen. The velocity of the last two reactions will be accelerated by the enormous pressures to which all oils must be subjected when buried in the interior of the earth. Though we have at present no exact data in regard to the velocity of the foregoing secondary reactions, there are enough available to show that the sum of the three is amply sufficient to prevent the accumulation of detectable amounts of free hydrogen or unsaturated hydrocarbons below temperatures of 300°. Accurate information as to the mechanism involved in the formation of di- or tri-cyclic naphthenes is not yet forthcoming. Many reactions besides the one mentioned can be suggested and shown to be consistent with the rules of organic chemistry.

With the progress of time, the accumulation of cyclohexane and its derivations must necessarily increase. A certain proportion of these will become partially unsaturated and rearrange themselves to form polycyclic compounds; another portion will be completely dehydrogenerated to yield benzene or toluene. These should make their appearance in the oldest type of petroleum, the asphaltic base. Oldest here signifies farthest removed from the original "protopetroleum" and does not refer to time, as there are numerous geological factors which would determine the temperature of any particular underground region.

COMPOSITION OF PETROLEUM CHANGES WITH TIME

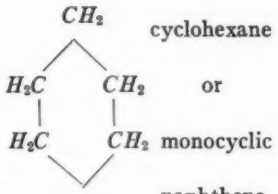
Carrying along the analogy of low temperature cracking in a bomb still further, it ought to be possible to predict the ultimate fate of our hydrocarbon material. Besides the known physical-chemical facts relating to petroleum hydrocarbons, we have the principle of Le Chatelier to guide us. So far as is known, the rate of the primary decomposition is a function of temperature alone, although investigation in the future may show that the great pressures found in oil beds also exert an influence, and, if so, will probably be found to increase the rate of decomposition. Among the products of decomposition occur saturated paraffines with one carbon atom less than the original molecule. This again decomposes, but at a lesser rate, because stability increases with decreasing molecular weight. There is thus an accumulation of light gaseous hydrocarbons with a high hydrogen-carbon ratio on the one hand and on the other, liquid and solid hydrocarbons becoming ever poorer in hydrogen. The influence of pressure will be such as to favor the formation of dense hydrocarbons in the form of ringed compounds. There is a contraction of molecular volume of 12 units when amylene is converted to cyclopentane and 16 units in the case of hexylene to form cyclohexane (23). Dense saturated molecules with a low hydrogen-carbon ratio, such as the polycyclic naphthenes, are produced to greater and greater extent. These form the high molecular weight and semi-solid substances found in asphalts. No correspondingly high molecular weight paraffines are found, the highest so far isolated being no greater than those found in the vegetable tissues mentioned at the beginning.

This can be made clear by the following illustrative reactions.

1. $CH_2=CH-CH_2-CH_2-CH_2-CH_3$

normal hexyalene or monoolefin

D_4^2 0.683



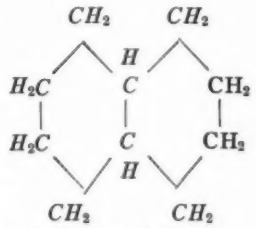
cyclohexane or monocyclic naphthene

D_4^{20} 0.779

2. $CH_2=CH-(CH_2)_5-CH=CH-CH_3$

normal decylene or diolefin

D_4^{20} 0.710 (approx.)



hydro napthalene or dicyclic naphthene

D_4^{20} 0.934

Similarly a straight chain hydrocarbon of the series $C_nH_{2n}-4(n>14)$ with three double bonds, formed from the corresponding saturated hydrocarbon through the loss of hydrogen, can condense into a molecule with a tricyclic ring. In such a manner as this it is possible for even four and five cyclic hydrocarbons of high molecular weight to be formed, having physical properties similar to those compounds which must exist in heavy oils and asphalts. The possibility of simpler rings coalescing to form more complex rings must not be overlooked.

As stated before, there is plentiful evidence that the cyclization process, being an intramolecular rearrangement, takes place with great rapidity. Also if coalescence of rings takes place, the probability of its occurrence will increase with time because of the increase in concentration of the ring molecular species. Quite the contrary will take place in regard to the production of long hydrocarbon chains giving rise to paraffine compounds of higher molecular weight. Why this should be so will be clear from the following argument. The existence of the free ethyl radicle has been definitely proved by Paneth (24) and others. It is conceivable that high molecular weight alkyl radicles might be formed and then these combine to form other paraffine compounds containing more than, say, 35 carbon atoms to the chain. But

with increase in length of chain comes increase in probability of cision and loss of hydrogen to form olefines, followed by cyclization. Hence these two factors would operate against the accumulation of large amounts of high molecular weight paraffines, all of which accords with experiment.

It is further to be expected that the longer the heat treatment, the more the cyclic hydrocarbons should be in evidence and the earlier in the series of ascending molecular weights should the di- and tri-ringed compounds make their appearance in fractions having nearly equal boiling points. It is interesting in the light of the theory put forward to compare the structure of the hydrocarbons found in the various petroleum fractions going from east to west. Thus the molecule containing 15 carbon atoms belongs to the C_nH_{2n+2} series in Pennsylvania petroleum, to the C_nH_{2n} in Ohio petroleum, et cetera. This is shown in a condensed form in Table III.

TABLE III

Number Carbon Atoms in Molecule	*Name of Petroleum*				
	Penn.	*Ohio*	*Texas*	*Alberta*	*California*
C_{15}	C_nH_{2n+2}	C_nH_{2n}	C_nH_{2n-2}	C_nH_{2n-2}	C_nH_{2n-2}
C_{20}	C_nH_{2n}	C_nH_{2n-2}	C_nH_{2n-4}	C_nH_{2n-4}	C_nH_{2n-4}
C_{25}	C_nH_{2n} C_nH_{2n-4}	C_nH_{2n-4}	C_nH_{2n-4}	C_nH_{2n-4}	C_nH_{2n-4}
C_{30}	C_nH_{2n-4}			C_nH_{2n-6}	C_nH_{2n-8}

Ultimately a point must be reached where the hydrocarbon material is all in the form of a gas and a semi-solid material so viscous, owing to its high carbon content, that it will no longer flow. Such oil fields will yield only gas and no liquid oil. This condition will exist in all those fields where the bituminous material is of very ancient origin and has been buried at such a depth that the temperature has been more than 200°C. Thus the maximum depth of oil wells should never exceed 20,000 feet. In time the semi-solid remains, if still under the influence of heat, will lose all of its hydrogen and then become a natural form of petroleum coke. A mineral corresponding with this has been found and is classified under the name, anthroxalite.

Whether the compounds of sulphur which occur in petroleum have come from the original material or have been formed afterward through the action of hydrogen sulphide is a difficult question to answer. It is possible the nitrogen compounds are derived from protein material which accompanied the original fats. Similarly, the phenols which are usually present to a small extent, have probably been formed through rearrangement from the ketones that have been formed in turn from the fatty acids or their lime soaps.

An explanation of the large pressures often encountered in oil fields is also suggested by the theory. The "protopetroleum" has at first a very small vapor pressure. With the formation of lighter hydrocarbons through low-temperature decomposition this vapor pressure increases. Finally large amounts of the fixed gaseous hydrocarbons accumulate and these, if they can not escape, build up a high pressure. An idea of the maximum pressure which might be built up under such circumstances can be obtained by the following calculations. Assume that the average molecular weight and composition of the "protopetrolic" material can be represented by $C_{17}H_{36}$ and that the perfect gas law applies. Then, the final stage can be represented thus:

$$C_{17}H_{36} \rightarrow 9CH_4 + 8C$$

The specific gravity of heptadecane is given as 0.7766 at 22.5°C. and that of gas carbon as 2. Therefore 1 gram molecule of the hydrocarbon occupies approximately 310 cubic centimeters, and 8 of carbon occupy 48 cubic centimeters, leaving 262 cubic centimeters for the 9 molecules of methane. By assuming $p_1v_1 = p_0v_0$, the pressure acting on the methane due to the thermal transformation of the original pressure alone, becomes 769 atmospheres. The pressure built up on the assumption that other lower members of the paraffine series are produced can be calculated in a similar manner and is given in Table IV.

TABLE IV

	Hydrocarbon Formed	*Pressure in Atmospheres*
1. $C_{17}H_{36}$	$9CH_4+8C$	769
2. $C_{17}H_{36}$	$6C_2H_6+5C$	514
3. $C_{17}H_{36}$	$4\frac{1}{2}C_3H_8+3\frac{1}{2}C$	349
4. $C_{17}H_{36}$	$3\frac{3}{5}C_4H_{10}+3\frac{1}{5}C$	206
5. $C_{17}H_{36}$	$3C_5H_{12}+2C$	169

This pressure of course is exclusive of whatever pressure might be on the oil due to the overlying strata et cetera. As the critical temperature of propane is 153°C., it and the heavier hydrocarbons would quite probably be in the liquid condition, which would of course modify the foregoing calculations. Because of the commercial importance of cracking and hydrogenation, many data are being obtained on the physical-chemical reactions of petroleum hydrocarbons. When sufficient information is at hand on this phase of petroleum chemistry and when the kinetics of polymerization are more thoroughly understood, it may become possible from the presence of certain compounds in petroleum to calculate its age and the temperatures to which it has been subjected.

In conclusion it may be of interest to point out that a similar idea

to the one presented has been put forward in the case of the formation of coal, particularly as far as the bituminous content is concerned. Thus in the words of Hans Tropsch: (1)

The conversion of the wax of the brown coal bitumen into the hydrocarbons of bituminous coal bitumen can be explained by a kind of pressure distillation, as has been shown by the experiments of Erdmann.

BIBLIOGRAPHY

1. Hans Tropsch, "Problems in Chemistry of Coal," *Chem. Reviews*, Vol. 6 (1929), p. 63.
2. Benjamin T. Brooks, "Chemical Considerations Regarding Origin of Petroleum," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 6 (June, 1931), pp. 611–27.
3. Chas. F. Mabery, "The Solid Paraffin Hydrocarbons That Collect in Oil Wells in Pennsylvania," *Amer. Chem. Jour.*, Vol. 33 (1905), pp. 285–91.
4. F. Kraft, "Ueber fractionierte Destillation der höheren normal Paraffine aus Braunkohle im Vakuum des Kathoden Lichts," *Ber. d. deutsch. chem. Ges.*, Vol. 40 (1907), p. 4779.
5. G. Krämer and A. Spilker, "Das Wachs der Bacillariaceen und sein Zusammenhang mit dem Erdöl," *Ber. d. deutsch. chem. Ges.*, Vol. 32 (1899), p. 2940.
6. Reinhardt Thiessen, "Origin of the Boghead Coals," *U. S. Geol. Survey Prof. Paper 132* (1925).
7. G. Stadnikoff and A. Weizmann, "A Contribution to the Knowledge of the Transformations of Fatty Acids in the Course of Geologic Periods," *Brennstoff Chem.*, Vol. 10 (1929), 61–3, 581–82.
8. Frederick B. Power and Frank Tutin, "Chemical Examination of Aethusa Cynapium," *Jour. Amer. Chem. Soc.*, Vol. 27 (1905), p. 1467.
9. Hooper and Arnott. See Beilstein, *Handbuch der Oarganischen Chemie*, 4th ed. (1918).
10. A. Etard, "Des principes qui accompagnent la chlorophylle dans les feuilles," *Compt. Rend.* Vol. 114 (1892), pp. 364–66.
11. Lewis A. Thayer, "Bacterial Genesis of Hydrocarbons from Fatty Acids," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 4 (April, 1931), pp. 441–53.
12. R. F. Ruttan and M. J. Marshall, "Adipocere," *Jour. Biol. Chem.* Vol. 29 (1916), p. 319.
13. Warren and Storer, *Mem. Amer. Acad.* (2), Vol. 9 (1865), p. 208. See Bacon and Hamor, *American Petroleum Industry*, p. 11.
14. C. Engler, *Ber. d. deutsch. chem. Ges.*, Vol. 21 (1888): "Zur Bildung des Erdoels," *Zeit. für angew. Chem.*, Vol. 21 (1908).
15. C. D. Hurd, *The Pyrolysis of Carbon Compounds*.
16. R. E. Burk, "Thermal Decompositions of Straight Chain Paraffins," *Jour. Phys. Chem.*, Vol. 35, No. 8 (1931), p. 2446.
17. M. Polyani and E. Wigner, "Ueber die Interferenz von Eigenschwingungen usw.," *Zeit. physik. Chem.*, A., Vol. 139 (1928), p. 439.
18. H. I. Waterman and J. N. J. Perquin, "Decomposition of Paraffin Wax at 450° in Presence and in Absence of Hydrogen under High Pressure," *Jour. Inst. Petrol. Tech.*, Vol. 11 (1925), p. 1136.
19. H. Gault and F. A. Hessel, "Dissociation pyrogénée de l'Hexadécane," *Ann. Chim.*, Vol. 2 (1924), p. 319.
20. Stephen Kiss, "Destructive Hydrogenation in Bomb-Polymerization in Cracking," *Ind. Eng. Chem.*, Vol. 23, No. 3 (1931), p. 315.
21. Charles G. Maier and Stuart R. Zimmerly, "The Chemical Dynamics of the Transformation of the Organic Matter to Bitumen in Oil Shale," *Bull. Univ. Utah*, Vol. 14, No. 7 (62).
22. W. Ipatiev, "Catalytic Reactions at High Temperatures and Pressures," *Jour. Russ. Phys.-Chem. Soc.*, Vol. 38 (1906), pp. 63–75.
23. Julius B. Cohen, *Organic Chemistry*, Vol. II, p. 13. Edward Arnold Co., London, 5th ed. (1931).
24. Fritz Paneth and Wilhelm Hafeditz, "Ueber die Darstellung von freien Methyl," *Ber. d. deutsch. chem. Ges.*, Vol. 62 (1929), p. 1335.

DISCUSSION

K. C. HEALD, Pittsburgh, Pennsylvania (written discussion received, June 17, 1933): In his introduction, on the first page, Mr. Seyer states:

> There is thus left behind a semi-solid mass of waxy material, which is in time converted into soaps or salts of calcium and magnesium. Such residual substances have been found in damp places and have been given the name adipocere. The wide occurrence of these remains of adipose tissue, in beds whose age can easily be determined, is itself a proof of the stability of the fatty acids.

This statement gives the impression that soaps or salts of calcium or magnesium have been found in fossil sediments—in fact, that they are not uncommon. I have no knowledge of any such occurrence nor can I find any reference to any such occurrence in the literature. The only thing even approximating such an occurrence is the reference given by Mr. Seyer himself to material which is a result of about sixteen years decomposition and modification in sea water.

Mr. Seyer has a discussion under the heading "Composition of Petroleum Changes with Time." Though geologists would agree with his conclusion that the end product of petroleums will be gas and solid hydrocarbons, the evidence is all against a progressive increase in the specific gravity of petroleum, which suggests that his reasoning is faulty. I feel that he has failed to investigate the gravity-age relationships of petroleum in the known fields of the world.

In the four paragraphs preceding the concluding paragraph is a brief discussion of the pressure in oil fields, wherein Mr. Seyer assumes that it is possible to compute the pressure that would be built up by thermal transformation, and the inference is that the pressures would be substantially in excess of hydrostatic pressure—a conclusion which does not agree with observation, since pressures in excess of hydrostatic are comparatively rare in so far as my records indicate.

W. F. SEYER (written discussion received, August 14, 1933): In reply to Mr. K. C. Heald's discussion of the paper I should like to state that the term "recent beds" instead of merely "beds" might have been more appropriate. A knowledge of the composition and occurrence of adipocere can be obtained from almost any treatise on fats and waxes. The material investigated by Ruttan and Marshall (Ref. No. 12) consisted of the fatty remains of a pig estimated to have been buried for 45–47 years. Waxy material of this kind has often been found in old cemeteries. Besides the name adipocere leichenwachs, cera cadaverica, and bog butter have been used to designate these waxy remains of adipose animal tissue. For further information see:

1. W. Gregory, *Ann. Chem.*, Vol. 61 (1847), p. 362.
2. Ebert, *Ber. chem. Ges.*, Vol. 8 (1875), p. 775.
3. L. Schmelck, *Chem. Zeit.*, Vol. 26 (1902), p. 11.
4. C. D. Wetherill, *Jour. prakt. Chem.*, Vol. 68 (1856), p. 26; *Trans. Amer. Phil. Soc.*, Vol. 11 (1860), p. 91.
5. N. Torugi, *Chem. Zentr.*, Vol. 1 (1905), p. 683.

Mr. Heald refers to the paragraphs under the subtitle, "Composition of Petroleum Changes with Time." Briefly what is meant is this. The bulk of the protopetroleum material becomes denser, owing to the formation of ringed compounds. Simultaneous with this is the production of a smaller amount of paraffine hydrocarbons, which go to form the gaseous or light boiling fraction of petroleum. These fractions will contain normal as well as iso-

paraffine hydrocarbons and ringed compounds such as simple derivatives of cyclohexane, et cetera. The theory predicts that, because of the increasing stability of the hydrocarbons with decreasing molecular weight, these fractions should become still less dense with time and ultimately, in the ideal sense, end with methane. The material following the other branch must become denser with time, giving rise to a certain amount of light hydrocarbons during the transformation process and it, in its turn, ending with a coke-like product. This must be the fate of the bulk of the material. What I wish to emphasize is that from the chemical point of view the asphaltic or ringed hydrocarbons must come from the paraffinic hydrocarbons and not the reverse. It is thus possible that Mr. Heald's observations deal with oil from which the heavier fractions have been separated in some manner.

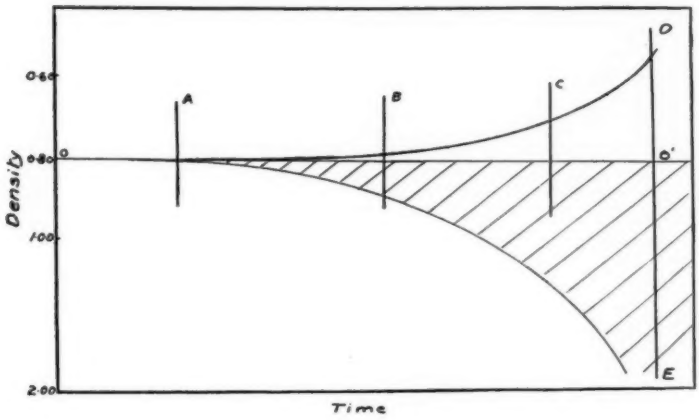


FIG. 1

The change in composition with time may best be illustrated by the appended diagram (Fig. 1). At the point *O* the density of the protopetroleum may be assumed to be about 0.80. Then the shaded section lying below the line *OO'* will represent that fraction of the original material which is becoming denser with time, the line *OE* being the average density; similarly for the light fraction above the line *OO'*.

If a well is sunk at age *A* a paraffine-base oil should be encountered, whose density will be about that of the original material. Oil found at *B*, however, should be a mixed paraffine asphaltic base. Here a number of possibilities present themselves, depending on whether the light and heavy fractions have remained together. At *C* an asphaltic base petroleum should be obtained. Here again if the oil comes from the lighter fraction it will be lighter than that at *B*; for the heavy fraction the reverse will be the case. Even if the two fractions occur together, there will be a tendency toward separation because of the decreasing solubility of the high molecular weight hydrocarbons in the petrol ether fraction, that is, the low boiling fraction. At *D* only gas will be released as the heavy fraction will be too dense to flow freely.

In regard to the pressure developed in oil fields I should like to refer Mr. Heald to the paper of R. W. Pack on the "Sunset-Midway Oil Field, California, Part I, Geology and Oil Resources," *U. S. Geol. Survey Prof. Paper 116* (1920), p. 84. I have also requested Professor Williams to give a brief account of his experience in the Turner Valley field. In the present July number of *World Petroleum*, page 8, the Attock Oil Company of India reports pressures as high as 5,000 pounds per square inch.

M. Y. WILLIAMS, professor of paleontology and stratigraphy, University of British Columbia, Vancouver, B. C. (written discussion received, August 14, 1933): The conclusions reached in Dr. Seyer's paper are fully supported by my field observations. For instance, in the Ontario oil fields, petroleum has been obtained from middle Devonian, middle Silurian, and middle Ordovician formations, and the oil has decreasing specific gravity in the order named—that is, the Devonian oil varied from 33–40° Bé., the Silurian was about 38–41° Bé., and the Ordovician (Trenton) was obtained as a drip from large gas flows and was virtually casing-head gasoline. The same conditions hold in general in the Turner Valley, Alberta, where crude oil occurs in Cretaceous formations and the very light oils (about 72° Bé.) occur with immense flows of gas in or near the top of the Paleozoic limestone.

The gas pressure met with in the deep wells of Ontario and Alberta are most satisfactorily explained by Dr. Seyer's conclusions, as in neither case is water found in common association with the hydrocarbons and hydrostatic head appears to be absent.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 10 (OCTOBER, 1933), PP. 1268-1270, 1 FIG.

GEOLOGICAL NOTES

IGNEOUS INTRUSIVES IN SILVER CITY AREA, KANSAS

The observations of Robert Hay[1] upon the occurrence of a dark blue rock in seams 1–12 inches thick, intrusive in Pennsylvanian shales in the Silver City metamorphic area of Woodson County, Kansas, apparently were not confirmed by the later investigations of Twenhofel,[2] and Twenhofel and Edwards,[3] although these authors ascribed the metamorphism of the rocks of the locality to the action of igneous intrusives probably occurring some depth below the surface. In 1929 the writer observed fine dark blue and also coarse gray quartz rocks occurring as scattered fragments in the soil near one of the old mining shafts; microscopic examination indicated their igneous origin. These loose fragments of igneous rocks appear to be distributed in a narrow belt several feet wide, extending east-west, essentially parallel with a zone of fractured and sharply tilted beds.

An excellent summary of the literature on the Silver City and adjacent Rose Dome areas is given by Knight and Landes,[4] to which the reader is referred. This note is merely for the purpose of briefly describing the igneous rocks occurring at the surface in the Silver City area, and confirming the observations published by Hay in 1882, when the rocks in the exploration shafts were well exposed to view.

Two kinds of igneous rock are represented in the loose fragments in the soil. One is a dark-colored dense aphanite, shown in Figure 1, the weathered surface showing a distinct globular or spheroidal texture characteristic of volcanic rock. The spheroids surrounded by rims range from 1 to 10 millimeters in diameter. Below the weathered surface the spheroids appear as dark spots. It was probably this type

[1] Robert Hay, "Igneous Rocks of Kansas," *Trans. Kansas Acad. Sci.*, Vol. 8 (1882), pp. 14–18.

[2] W. H. Twenhofel, "The Silver City Quartzites," *Bull. Geol. Soc. Amer.*, Vol. 18, pp. 419–30.

[3] W. H. Twenhofel and E. C. Edwards, "The Metamorphic Rocks of Woodson County, Kansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 5 (January–February, 1921), pp. 64–74.

[4] G. L. Knight and K. K. Landes, "Kansas Laccoliths," *Jour. Geol.*, Vol. 40 (1932), pp. 1–15.

of rock that Hay[5] described as occurring in seams in the sedimentary formation exposed in the shaft. Microscopically it is porphyritic, both phenocrysts and the spheroids being enclosed in a fine-grained chloritic groundmass. The phenocrysts, probably originally feldspar, are much changed to green chlorite, epidote, and several colorless minerals probably including some fibrous quartz and zeolites.

The dark aphanitic rock appears to be completely altered, but its macroscopic appearance as well as the crystal form of phenocrysts in the groundmass indicate its igneous origin.

FIG. 1.—Fragment of spheroidal igneous intrusive.

The light-colored rock is coarse-grained, with coarse quartz in blebs and stringers ranging from 1 millimeter to 2 centimeters in thickness. The amethystine quartz observed by Mudge[6] and Hay[7] is probably represented by this type of rock. Under the microscope it is seen to contain much orthoclase, both the quartz and orthoclase containing much fibrous actinolite? and some epidote and apatite. Much of the actinolite? and epidote occurs in radiating aggregates. The needles of actinolite (inclined extinction and positive elongation) extend from the borders out into the quartz, and form veinlets in the quartz.

[5] *Op. cit.*

[6] B. F. Mudge, "Metamorphic Deposit in Woodson County," *Kansas Acad. Sci.*, Vol. 7 (1880), pp. 11–13.

[7] Robert Hay, *op. cit.*, pp. 14–18.

The coarse quartz-orthoclase rock is apparently not a normal igneous rock but a pegmatitic phase. The black dense porphyritic aphanite is probably a normal igneous intrusive. Both phases were chloritized and epidotized during the later stage of hydrothermal action accompanying the magmatic intrusion. The silicification of the surrounding Pennsylvanian sandstone in the Silver City area to quartzite is interpreted as accompanying effects of the hydrothermal action.

The writer has observed veinlets of actinolite? in quartz in brecciated phases of the pegmatite dike of the near-by Rose Dome area indicating, as should be expected, a close association in the intrusive phenomena of the two localities.

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September 2, 1933

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DISCUSSION

PRESERVATION OF OIL DURING EROSION OF RESERVOIR ROCKS

In his paper published in the July *Bulletin*[1] Dorsey, discussing as a class those oil fields of the United States which are productive from porous rocks below unconformities of major importance, states his belief that "an impartial survey of the geological data affords no evidence either that the oil was formed in post-unconformity time or was introduced at a later date. . . . If this belief is accepted," he continues, "the problem of preserving the oil during exposure and erosion of its reservoir rocks must be squarely faced." He then undertakes to point out a protective mechanism.

Not only is the present writer unconvinced as to the practical effectiveness of Dorsey's protective mechanism, for the preservation of pre-unconformity oil and gas pools, but he must refute the major premise of Dorsey's paper by citing the Kevin-Sunburst field of Montana as an example of post-unconformity oil accumulation. Apparently there can be no other conclusion than that the porosity of the upper portion of the Madison limestone (Mississippian) which contains the greater portion of the oil was developed during a non-deposition and erosion period made up of all Pennsylvanian, Permian, and Triassic time. This oil and the additional oil found in the contact debris and in the basal sands of the succeeding Ellis formation (Jurassic) could not have been trapped in other than post-unconformity time.

Some reasons for believing that Dorsey's protective mechanism for preservation of oil during erosion of its reservoir rocks has failed to operate to an important degree are, briefly, the following.

1. Oil which has floated on the ground water would be reduced to low gravity by evaporation and alteration. The oils of the unconformity pools are not characteristically low in gravity.

2. Trask's objection that during the initial stages of post-unconformity submergence the water beneath which deposition would be occurring should be able to flood the porous reservoir rocks, permitting the escape of any oil in the latter.

Dorsey recognizes this as a formidable objection and thinks it "would obviously happen unless the eroded ends of the reservoir rocks had been sufficiently clogged to prevent the entrance of water. Clogging," he continues, "could be caused by terrestrial deposition or by an oxidized petroliferous residue in the sands through which the oil had passed twice."

Such clogging could be effective in the case of higher dips where the eroded end of a reservoir bed would offer small area of egress, but the present writer is unable to place much reliance in the efficacy of such processes where the dips are low and the area of truncation is consequently large. Moreover, clogging caused by asphaltic residue would leave conspicuous amounts of

[1] Geo. Edwin Dorsey, "Preservation of Oil During Erosion of Reservoir Rocks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 7 (July, 1933), pp. 827–42.

such material, including oil in all stages of inspissation and alteration, which have not, so far as known, been encountered in developing unconformity oil fields.

Unconformity oil pools of post-unconformity age do exist and these obviously require no protective mechanism for their preservation. With reference to the protective mechanism as a geologic process, the objections here presented may, to an impartial critic, appear no more meritorious than the argument of the proponent, the inherent weakness of both being impossibility of direct observation and lack of experimental data. It would seem that the subject would lend itself to experiment.

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As Irwin's idea of "the major premise" of my article differs from mine, I shall restate it here. I endeavored to point out a method which it seemed to me *could* prevent the escape of pre-unconformity fluids, including oil, from porous, pre-unconformity rocks during truncation of the latter, at the same time emphasizing the lack of definite evidence in the rock section as to whether the oil actually did form before or after the unconformity.

Irwin's citation of the Kevin-Sunburst field as a relevant example of the type of unconformity field discussed in my article indicates that I should have made a specific exception of all those fields where the oil formation and accumulation are obviously and clearly of post-unconformity age.

The fields I discussed are those in which the pre-unconformity series contains everything necessary for the formation of an oil pool,—source material, porous rocks, favorable structure. Where these exist it seems to me a problem is raised regarding the preservation during truncation of any oil which might have formed during the practically complete geological cycle represented in the pre-unconformity primary uplift. Obviously this is not the case where the pre-unconformity series, as at Kevin-Sunburst, does not contain porous reservoir rocks. In non-porous rocks no fluids can be present to require preserving, or to be lost, or to raise any problem whatever. If the porosity of the Madison limestone results from leaching during the erosional period, and if there were no porosity before leaching, I readily admit that any fluids now in the limestone entered after porosity was developed, that is, in post-unconformity time.

More striking examples than even Kevin-Sunburst of post-unconformity formation and accumulation of oil are the granite and granite-wash oil occurrences in the Amarillo district of the Texas Panhandle.

I can not see, however, that consideration of these fields is relevant in a discussion of the type of oil occurrences dealt with in my paper.

So little is known of the physical and chemical factors which determine the gravity of oil, it is largely a matter of personal opinion what the gravity of oil might be after having been exposed in the earth to any particular combination of physical and chemical conditions. Experimental data on this would indeed be welcome.

I am at a loss to know what criteria Irwin invokes in arriving at a conclusion regarding the dividing line between the rate of dip and the consequent width of outcrop of porous rocks where terrestrial deposition and

petroliferous residues will afford sufficient clogging to keep the waters of post-unconformity seas out, and the rate of dip and width of outcrop in which these clogging factors will be inoperative. For example, what criteria does he use in determining that clogging agencies will be effective in beds dipping 5° but not in beds dipping 10°? His criticism here again seems to be largely a matter of personal opinion.

It is a matter of fact that asphaltic residues are commonly encountered in drilling unconformity fields of the type I discussed. The Maricopa Flat field in California is cited in the article. Coalinga also has asphaltic residues which have a clogging effect strong enough to hold the oil below underground fluid level under considerable pressure. This also is noted in the article. One of the earliest wells drilled by the Indian Territory Illuminating Oil Company at Oklahoma City blew clouds of black asphaltic material into the air in large amounts. This came from the unconformity. The souvenir postal cards on sale at the news-stands in Oklahoma City show this well blowing clouds of this asphaltic material, although the cards state the black clouds are oil. I cite this to indicate the conspicuous amounts of asphaltic material encountered. Some asphaltic material is obtained at the unconformity in practically every unconformity field of the type I discussed. In the light of these facts, Irwin's statement, "Moreover, clogging caused by asphaltic residue would leave conspicuous amounts of such material, including oil in all stages of inspissation and alteration, which have not, so far as known, been encountered in developing unconformity oil fields," is not correct.

GEO. EDWIN DORSEY

DALLAS, TEXAS
August 23, 1933

In his paper Mr. Dorsey has attempted an explanation of the occurrence of oil below unconformities. He suggests the formation of the oil in the reservoir rocks prior to uplift and erosion and outlines a possible protective mechanism for its preservation. Such protective mechanism, he states, would consist mainly of the action of gravity which causes the sinking of the ground-water table during uplift. There must also be considerable depth to the underground fluid level when submergence occurs. Further, the rate of deposition of post-unconformity beds compared with rise of oil level toward eroded ends of reservoir rocks must be so great that an impervious cover is formed before the oil is raised to the eroded surface. This implies almost catastrophic subsidence because the eroded surface must be depressed below the ocean and tightly sealed before influx of ocean water and rise of ground-water table can flush out the gas and oil.

In discussion of the geochemical and geophysical factors involved, Mr. Dorsey states: "When the reservoir rocks were ultimately pierced by erosion there could be no hydrostatic pressure on the gas. There might even be a partial vacuum." This last statement is true only if the formation was completely sealed and the oil level tended to sink with the ground-water level to lower parts of the structure. If the oil reservoir was originally buried 1,000 feet and filled with gas and oil, under normal conditions the gas pressure would be about 430 pounds per square inch. If the gas sand was 20 feet thick and no lateral expansion occurred, it would be necessary for the water of the formation to effect a vertical drop of 600 feet in order to produce a vacuum.

During this process the gas would expand to 30 times its original volume, presumably without migration into adjacent formations. Where would the water of the formation go as it sank away from the entrapped oil and gas? It is evident that by the time erosion exposed the reservoir the uplift would have to be in the neighborhood of 600 feet.

Dorsey says that fresh water could and did enter these outcrops. He cites several examples of such dilution which is shown by an increase in the dissolved solids in water down the dip from outcrops. He argues that the oil is retained in the eroded ends of the formation by sinking of the ground-water level during uplift. During this time some fresh water entered the formation. This fresh water, which he says by-passed the oil, entered much too quickly for the oil to escape. After this brief period of influx the formation was sealed. After sealing, additional uplift would allow no more fresh water to enter and sinking of the oil and water might produce the vacuum as illustrated.

The idea requires too many special conditions. Observations point to the conclusion that if meteoric water can enter an outcrop, even for a brief geologic time, then it provides a medium for the escape of most of the oil and gas in a formation. One outstanding example of this principle occurs on the north flank of the Arbuckle Mountains in Oklahoma. It is known by water analyses that fresh water entered this outcrop and traveled down the dip a distance of approximately 15 miles. Also, within this diluted zone, no oil occurs except on small folds on the slope of the major one. Thus the infiltrating fresh water by-passed the oil not by sinking through it, but by going around it. There seems to be no doubt that most of the oil was lost at the outcrop.

A fundamental error in the cycle constituting the protective mechanism for the preservation of oil during erosion of reservoir rocks is the assumption that the ground-water level in an uplift lies below the lowest point on the surface. It is an elementary principle in hydrology that permanent streams lie at the ground-water table. They are fed by lateral flow from higher portions of the water table under the near-by hills. In any uplift having permanent streams the water table must be higher than the erosion channels. Oil floating on this water table would escape to the valleys and be lost. Mr. Dorsey's figures show erosion removing the reservoir by horizontal planation or peneplanation. Normal erosion produces irregular surfaces at first, with peneplanation as the final stage. Peneplanation can only be accomplished by sluggish, meandering streams flowing at ground-water level. Such conditions would provide abundant time and ideal conditions for the complete removal of all gas and oil from the reservoir.

There is much evidence in support of the theory that such uplifts were zones of intake and that the mineralized water in the oil-bearing formations was diluted from the outcrops. However, proof of this process seems to offer no evidence on the side of the argument that the oil in the unconformity fields is pre-unconformity in origin. In fact the preponderance of the evidence asserts itself in refutation of such contention.

Mr. Dorsey's discussion on the mineralization of the water is open to considerable modification. He assumes a great deal of secondary concentration of the waters. In this he is supported by the consensus of opinion which is based on considerable observational evidence. However, he attributes this secondary concentration to "increased heat and pressure which greatly

increase the ability of water to dissolve salts" and states further that the salts were thus leached from the enclosing rocks. The pressure factor can not be credited with aiding the leaching thus assumed. The *International Critical Tables*, Vol. 4, p. 265, state that the solubility of sodium chloride is increased only 0.78 per cent with an increase of pressure from 0 to 1,500 atmospheres, corresponding to a depth of 50,000 feet or 9 miles. Thus, at 1,500 atmospheres, a water normally having 150,000 p.p.m. of sodium chloride would contain approximately 151,170 p.p.m. This increase is scarcely within the limits of analytical error. The solubilities of some of the common salts are known to decrease with pressure and it seems safe to state that the effect of pressure on any of the salts present in the oil-field brines would be negligible. The dissolved solids in these brines are generally composed of more than 99 per cent of very soluble salts and their average concentration does not necessitate any increase in the dissolving power of the water. From what formations did the waters leach such salts? Salt deposits are not known in the lower formations of the Mid-Continent field. Yet these waters commonly contain as high as 250,000 p.p.m. of dissolved salts.

Mr. Dorsey believes that these brines may become supersaturated under the conditions of reduced heat and pressure during uplift and that precipitation of some of the dissolved salts may have caused secondary cementation of the sand. Also, he says that later burial and restoration of the heat and pressure might cause the waters to re-dissolve some of the previously precipitated cementing material, or salts. Perhaps the author is referring to the common cementing materials, silica, calcite, or dolomite. However, this possibility is apparently eliminated, since he writes "Some of the dilution of Ordovician waters noted may also be the result of such precipitation." Such statements demand correction. It may be stated as a matter of logic and of fact that the precipitation of all the silica and carbonates in average oil-field brines would not appreciably affect their concentration, since these salts rarely exceed 0.1 per cent of the total. Furthermore, the precipitation of salts from a supersaturated solution would still leave the solution saturated, no dilution thereby being apparent. The subject of mineralization, as set forth in this paper, seems irrelevant to the author's major thesis. Mr. Dorsey has herein suggested some revolutionary ideas which would indeed be welcome provided that they were justifiable in the light of known chemical and physical principles.

L. C. CASE

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September 9, 1933

There are a few points in Mr. Case's discussion of my article upon which I should like to comment.

He states that a vacuum could exist "only if the formation was completely sealed and the oil level tended to sink with the ground-water level to lower parts of the structure." He then postulates a case where there would be 430 pounds pressure per square inch on the gas. Obviously a reservoir must be sealed to hold such a pressure. It is equally obvious that an enclosed space which will contain pressures will also contain a vacuum.

Replying to his question "where would the water of the formation go as it sank away from the entrapped oil and gas?", the answer I would make is

it did not sink away. It was left behind at the connate fluid level as the rocks rose above this level. I picture the reservoir rocks rising above the connate fluid level in the way a volcanic peak emerges from the ocean, leaving the water level unchanged. The more than 600 feet of uplift required to cause a vacuum in Case's illustration is surely not an amount of uplift which would present a problem to earth forces which give abundant evidence of having brought about uplifts of more than ten times this amount. The amount of uplift is to be measured above the connate fluid level and not the surface of the ground. This question of whether a vacuum actually existed when the reservoir rocks were pierced by erosion is not a particularly important factor in the preservation of oil by the method I pointed out.

In the illustrations in my article the expression "connate fluid level" would have been better than "underground fluid level" because it would have prevented the confusion in which Case is involved in his discussion of "an elementary principle in hydrology." His remarks about the ground-water table are, of course, true, obvious, and elementary. The existence of a ground-water table, however, is dependent upon the presence of impervious rocks below the surface zone, which serve to hold the water table up to the level of the perennial streams. In the absence of such impervious rocks there would be an indiscriminate mingling of meteoric and connate fluids.

The reservoir rocks on an uplift of the type I discussed are porous across their outcrops unless the outcrops were clogged in some way, but the reservoir rocks have impervious rocks above and below them. The meteoric ground-water table will bend upward and cross the uplift near the surface where there are impervious rocks below the surface, as is well known, but across the exposed ends of the porous reservoir rocks this ground-water level will sink to the connate fluid level and porous rocks will constitute areas of ground-water intake. Elsewhere in his discussion Case admits this occurs when he says "It is known by analysis that fresh water entered this outcrop (the north flank of the Arbuckle Mountains in Oklahoma) and travelled down the dip a distance of approximately 15 miles" et cetera.

Case appears to have overlooked the impervious beds above and below the porous zone. Such beds separate the surficial ground-water zone from the connate fluid level, except across the outcrop of the porous rocks, and these impervious beds serve to make the ground-water table, *in so far as the connate fluids are concerned*, a perched water table. In drilling practice, surface pipe is set to take care of the ground-water table. This pipe is set in the underlying impervious rocks which act in the double capacity of holding the ground-water table up to the surface and separating it from the connate fluids below.

The illustrations were purposely drawn in diagrammatic fashion because it was believed that the details of the surface topography during the various stages of the erosional period represented by the unconformity, in addition to being unimportant to the general idea I was considering, would have had to have been pure assumption.

If Case had been specific regarding "the preponderance of the evidence" which "asserts itself in refutation" of the belief that oil may form before as well as after the unconformity, it would indeed have been desirable to have had it presented. As pointed out in my article, many geologists, including myself, have looked long and carefully and in vain for some geological evi-

dence which would date the period of oil formation in those rock sections which contain potentially oil-bearing beds both above and below the major unconformity which truncated and exposed the older rocks. The existence of specific preponderating evidence on this point is so "revolutionary" that the acceptance of such a belief can hardly be adopted upon the mere statement by Case that it exists.

I shall not make an effort to discuss the detailed chemical aspects of the secondary concentration of the connate water, because I am not qualified to do so. I believe, however, that there is ample chemical fact for the general statement I made that the "increase of pressure and temperature greatly increases the ability of water to dissolve salts." Case makes much of the fact that increase of pressure increases the solubility of sodium chloride but slightly. He has nothing to say about the other factor, increase of heat, and the great effect it has on the ability of water to dissolve salts. Case can not deny the accuracy of my general statement that heat and pressure together do increase the leaching ability of connate water, and the result of the combined action of the two factors was all I was interested in. His is a quantitative criticism. The source from which were derived the salts which the connate waters now contain has not been proved so far as I know. A geologist is likely to look to the enclosing rocks because a geologist is reluctant to postulate salt deposits all over the earth to explain the high mineralization of all the connate waters. Merely asking the question, as Case does, as to whence these salts come is adding nothing toward a solution of the problem of the origin of the salts. As a geologist, I would leave for quantitative chemical research the question of whether the rocks which enclose the connate water reservoirs are adequate to supply the salts found in the connate waters, but I would deny that the presence of large amounts of minerals in the connate waters of the earth must imply that these waters have been exposed to rocks of which we have no record, or are due to the action of underground migrating gases, or to underground evaporation, or to other forces of which we know nothing.

GEO. EDWIN DORSEY

DALLAS, TEXAS
September 11, 1933

REYNOSA PROBLEM OF SOUTH TEXAS, AND ORIGIN OF CALICHE

The writer desires to record, for the benefit of *Bulletin* readers, such discussion of this article, published in the May number (pages 488–522), as has been received from persons whose published work was quoted and who have been kind enough to permit the publication of excerpts from their letters.

The writer made no attempt, because the work was done at a point remote from geological libraries, to seek out the original worker in all the collateral fields which were drawn upon. Swinnerton disclaims any wish to be made to appear as the chief source of information on the subject of karst topography. As he says, the writer cited his work (and Douglas Johnson's) as an example of a group of articles on this topic, some of which are listed in his paper (Swinnerton, 1932).[1] Because of the same lack of library facilities, Trowbridge,

[1] References in parentheses are to the list of references of the original paper in the May *Bulletin*, pp. 520–22.

rather than C. L. Baker, was given as the source of the idea of deep alluviation of the Coastal Plain, resulting in the "drowning" of a pre-existing topography by river-borne sediments. Baker says (letter of July 7, 1933):

> In the second paragraph, page 492, you credit Trowbridge with my own original idea which I expounded at length in a letter to him while he was doing his field work, and which I first brought out in a report to Mr. Dumble late in the year 1913 (see the Rio Bravo files). My idea then was and now is that residual deposits had accumulated on all the land surfaces from the Gulf Coast to the Cordillera on a peneplain and then that the whole had been reworked, with uplift increasing toward the interior away from the gulf. The upwarp rejuvenated the drainage, causing the residual mantle to be shifted nearer the gulf. You will find I have published the idea under the heading Pleistocene Period in the chapter on Geologic History, University of Texas Bulletin 44, "Review of the Geology of Texas."

The writer stated[2] that no attempt had been made by him to compile a bibliography of caliche. Two items cited by Baker may be recorded here for the benefit of those compiling such a bibliography:

> We have all forgotten that classic work of Charles Darwin, *Geological Observations in South America*, published in 1846, which describes *tosca*, the South American name for caliche, in Argentina, Chile and Peru and, I think, correctly accounts for it. Bailey Willis in his book, *Northern Patagonia*, also discusses it.
>
> I suspect the first discussion of caliche in Texas is on pp. 29–32 of my "Geology and Underground Waters of the Northern Llano Estacado," University of Texas Bulletin 57, 1915, if it was not in W. D. Johnson's "The High Plains and Their Utilization."

Confirmation of two items of the writer's paper is given by Baker:

> In some cases I am pretty sure eolian deposits cover the caliche. Especially is this true in the marginal fingers of the High Plains. The base of the High Plains caliche on all margins has stalactites (p. 502, and Stage V, Fig. 3) depending from it.

Baker attributes to Brete Haigh the origin of the term, *siliche*, for "siliceous caliche," a usage suggested by Baker on page 722 of Bulletin 3232, Bureau of Economic Geology, University of Texas, 1933, where it is incorrectly printed "*silice*." The writer has not seen this publication.

Thornthwaite brings out a fuller statement of the close correlation between his climatic study and the distribution of caliche. The "P-E line of 48" which he mentions is the line between the "dry" and "wet" halves of the Sub-Humid zone shown by a line of dots in Figure 1, page 490. He says:

> One point which might be worthy of consideration in explaining the origin of caliche is that my P-E line of 48 (the line dividing the moisture-abundant from the moisture-deficient sub-zone of the sub-humid) is the line separating the region where precipitation exceeds evaporation from that where evaporation exceeds precipitation. In other words, west of the line P/E is less than 1, and east of it P/E is greater than 1.

This fact emphasizes the rôle of evaporation in the precipitation within the soil of the leached calcium carbonate, since the Reynosa caliche is shown in Figure 1 to lie on the arid side of the line.

Hawker writes that the writer's presentation of his (Hawker's) work was accurate, which is gratifying, in view of the extensive use made of this work and the incorporation of his theory of the origin of the age stages of soil-lime into the geologic picture presented by the present writer (pages 502–4, Figures 3 and 4, *et cetera*).

Fissures mentioned as occurring extensively in the caliche, page 495, have since been fully described by Barton in a paper entitled, "Surface Fracture

[2] Footnote 1, page 489.

System of South Texas."[3] These fractures seem, from his work, to be characteristic of the Reynosa Plateau. They are described in series having north-south, northeast-southwest, and northwest-southeast bearings and as being expressions of the fundamental, pre-Tertiary structural trends imposed upon the brittle caliche (which forms a competent group of strata) by shearing and possibly also by tensional forces. These fractures were first pointed out to the writer by Barton.

The lack of coördination too often existing between the work of scientists in the different fields of earth science is exemplified in letters from Hawker and Marbut. Hawker writes:

> The fact that the development of the caliche would be of such great interest to the geologist was unknown to me.

Marbut's letter, written at the writer's request that he review the paper, shows that the writer failed fully to credit him with fundamental work in the classification of soils and the recognition of the importance of caliche in this respect (Marbut, 1927). The isolation of the soil scientists (pedologists) and geologists is illustrated by the fact that Marbut, for many years, has recognized the Reynosa caliche as a soil product, without this idea having been brought to the attention of geologists of the Southwest.

Marbut contributes a discussion of the writer's suggestion that the term caliche be extended to include various types of rocks and minerals formed as accumulations in the soil. This discussion is most helpful and forms a basis on which an attempt to classify for the geologist the different types of soil-mineral accumulations might be made. Doctor Marbut, who has been at the head of the soil bureau of the Department of Agriculture since 1910, and who began his scientific career in the past century as a geologist, is well qualified to write of soil processes and materials for the geologist as well as for the pedologist. His letter (August 10, 1933) follows:

> I have your letter of July 25, and have also received your paper on the "Reynosa Problem of South Texas and Origin of Caliche." I have not had time to sit down and read the paper slowly and follow by a comprehensive study of the whole thing. I note, however, that you are concerned first, with the relationships of the Reynosa formation to the caliche underlying the so-called Reynosa Plateau, and in the second place, with the development of caliche. You are without question correct in ascribing the "limestone" underlying the Reynosa Plateau to a shallow subsurface accumulation due to soil developing processes. It is not a geological formation since it is not the product of deposition either of mechanical sediments or of precipitation of calcium carbonate in standing water. It is the product of accumulation of calcium carbonate, partly by washing calcium carbonate downward from the overlying material, and partly by converting calcium present in other forms than carbonate into carbonate through the process of weathering and the washing of this material down along with the carbonates and dropping them at the average level of penetration of rainfall in a region of low rainfall. To undertake to work out the stratigraphy of the region by considering this layer as one of the regular stratigraphic beds, undoubtedly encounters a great deal of difficulty and to this is due to a considerable extent, if not entirely, the problem of the Reynosa formation.
>
> For many years in discussing in my classes at Clark University and in the Graduate School of the Department of Agriculture, the pedology of the United States, I have described the Reynosa Plateau as a region protected from erosion by a limestone which itself is the product of soil developing processes and not a product of geological deposition.
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> The development of caliche or calcium carbonate accumulation layers in the soil profile

[3] This *Bulletin*.

has been a familiar matter to pedologists for a long time. In the original Russian work, the presence of such a horizon or layer was not emphasized, although its existence was recognized. Its presence was not used as a basis of soil classification. When, however, I was made chairman of the Subcommittee of Commission V of the International Society of Soil Science in 1924, and assigned the work of classifying the arid soils of the world, I adopted as a result of my studies, the presence of a developed caliche as a criterion for semi-arid and arid soils. Since that time I have used the presence of such a horizon as a basis of separating the soils of the United States into two great groups.[4]

Pedologists have not given much attention to the details of the development of the carbonate horizon. It is perfectly evident and has been well known to them for a long time that it represents the accumulation of carbonates in climates which are too dry to cause the entire elimination of these materials from the weathered zone. In the inspection of the Soil Survey work of Hidalgo County, Texas, with Mr. Hawker, several years ago, I suggested to him that I had never seen a region where the various stages of the development of this horizon were better illustrated than in the Hidalgo country. I suggested to him that he study the matter rather carefully and discuss it in his soil survey report and in other papers. This he did and so far as I know, it is the only paper that has discussed these various stages with equal fullness.

After you have given full consideration to the matter, I think you will abandon the idea of calling all of the soil horizons which may be ascribed to the accumulation of materials through the processes of soil development, caliche. The term, as you know, is a Spanish term and refers to the material accumulated by the processes of soil development in dry climates. It has been confined, therefore, to carbonate materials and materials more soluble than carbonates. It has never been applied to the sesquioxide materials[5] accumulated in the so-called *B* horizon of the humid soils. The reason why I think you will abandon this idea is that the processes of accumulation of the carbonates on the one hand, and the sesquioxides on the other, are entirely and fundamentally different. The carbonate material is accumulated in neutral and alkaline soils mainly, if not entirely, because of the evaporation of the water in which these materials were dissolved. The accumulation of sesquioxides on the other hand, cannot take place in a neutral or alkaline soil but takes place only in acid soils. These materials go into solution because of being adsorbed by dispersed and, therefore, acid colloidal materials, are carried downward until the unsaturated colloids become saturated and become electrically neutralized. They are then flocculated and because of flocculation are precipitated. Their electric charges may be neutralized by electrolytes or any other kind of material with a positive charge. The colloidal unsaturated acid organic matter always has a negative charge.

Because of the fundamental difference, therefore, in the process of accumulation of these two kinds of materials, I think you will finally conclude not to designate them all as caliche. If you designate these materials as caliche, you could with equal justification designate the iron crusts in the tropics as caliche and these are accumulated almost without any doubt by still another process than the two I have already mentioned. These iron crusts are ground water accumulations. While neither the caliche nor the sesquioxide accumulation already referred to has any relationship whatever to ground water, I should hesitate also to call laterites, kaolins, bauxites or chert, caliche. Kaolins and laterites especially, are nothing more than the products of the decomposition of silicate minerals. They are not the products of accumulation through soil developing processes but are wholly the result of the geological process of mineral decomposition. I should differentiate, therefore, between the shifting of materials that takes place in the processes of soil development and the mere accumulation of soil material through rock decomposition. I should be inclined to place chert and hornfels accumulation in a geological rather than pedological category also.

The accumulation of sesquioxides in regions of high rainfall has no relationship whatever to peneplanation complete or incomplete. They are wholly the products of the

[4] Marbut, 1927. See A. W. Weeks, *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 5 (May, 1933), pp. 472–73 and Fig. 3.

[5] "I am leaving out of consideration entirely the matter of accumulation of sesquioxides in the *B* horizon of soils through the operation of mechanical processes. There is little or no doubt but that such processes operate. The sesquioxide minerals involved in the accumulations of the *B* horizon are mainly sesquioxide of iron and sesquioxide of aluminium. In addition to these there is sesquioxide of manganese and probably also of titanium." C. F. Marbut, letter of September 2, 1933.

action of acid or adsorptive colloids, and the most effective colloids in this respect are those developed from decomposing organic matter. These processes will develop more rapidly under an approximately smooth surface but they will have no partiality for a smooth surface produced by peneplanation. These processes do not inquire before beginning their operation as to the process by which the smooth surface which permits their development was developed.[6]

Your discussion of the relationship of the caliche on the Reynosa Plateau to soil development processes is a real contribution to geology. Your generalization of all of the shifting and accumulation of materials which take place in the processes of soil development is well worth while. I think, however, when you study the matter somewhat further, you will not undertake to apply the term "caliche" to all of these accumulated bodies.—C. F. Marbut, letter of August 10, 1933.

W. ARMSTRONG PRICE

CORPUS CHRISTI, TEXAS
September 8, 1933

CORRECTION

In the article, "Reynosa Problem of South Texas, and Origin of Caliche," by W. Armstrong Price, in the *Bulletin*, Vol. 17, No. 5 (May, 1933), the following changes should be made and comments noted.

P. 507, line 6 from bottom, "non-calcareous caliche" should read: *non-calcareous sediments.*

P. 497, footnote 3, add: *The present usage is an extension of Dumble's Reynosa Plateau (1903).*

P. 520, line 4 from top, after "basins," add *some of which are.*

P. 521, reference 6 from bottom, asterisk (*) omitted before entry of C. F. Marbut's paper, which was not examined by the author.

RÔLE OF DIASTROPHISM IN TOPOGRAPHY OF CORPUS CHRISTI AREA, SOUTH TEXAS

CORRECTION

In the article, "Rôle of Diastrophism in Topography of Corpus Christi Area, South Texas," by W. Armstrong Price, in the *Bulletin*, Vol. 17, No. 8 (August, 1933), the following changes should be made and comments noted.

P. 911, line 9 from bottom, after "Crane Island" read: *Tactical Map, Corps of Engineers, United States Army.*

P. 913, Fig. 2, the letter *B* shown 11 miles northwest of the letter *G* in the word Galveston is illegible, appearing as a black dot in Galveston Bay.

P. 918, lines 17 and 18 from top, the word "behind" should read: *between.*

P. 921, line 9 from top, "depression" should read: *outlet.*

P. 930, line 3 of description of Figure 2, "Diameters" should read: *diameters* (making "Profiles" the subject of the verb "platted").

P. 933, line 6 of description of Figure 9, "1920" should be *1902.*

P. 936, lines 4 and 5 from bottom, last part of sentence should be transposed to read: *nearly all those bays which are round or equidimensional (Fig. 7) have a ratio of width to depth of 1 mile to 1 foot.*

P. 939, footnote 10, add: *Height of bluff at Port Lavaca, farther inland than Corpus Christi, is 19 feet.*

P. 941, line 19 from top, "and bone" should read: *clay.*

P. 943, Fig. 13, Gyp Hill is not located, being marked by dark timber south of the western lobe of Laguna Salada.

P. 947, Fig. 14, line 2 from bottom of description, after "current" read: *from the.*

[6] Woolnough's idea, and the writer's, was not that such deposits accumulate only under peneplains, but that they do characterize peneplains (as well as other surfaces of smaller area).

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 10 (OCTOBER, 1933), PP. 1282-1286

REVIEWS AND NEW PUBLICATIONS

"Discovery of Rock Salt Deposit in Deep Well in Union County, Arkansas." By H. W. BELL. *Arkansas Geol. Survey Inform. Cir. 5* (Little Rock, 1933), 21 pp., mimeog.; 2 figs.

Under the foregoing title the Arkansas Geological Survey has published, by photo-lithoprint reproduction, a complete account of the discovery of rock salt in the Smackover oil field. Mr. Bell, engineer for the Lion Oil Refining Company, supervised the drilling of the well in which the salt was found and his discussion of the geologic features involved and the mechanical difficulties encountered leaves little to be desired.

The first published announcement of the discovery of the Smackover salt, aside from routine reports in the trade journals, was made by W. C. Spooner in a geologic note in the June, 1932, issue of this *Bulletin*.[1] Geologic speculation and deduction are skillfully presented in this paper and Mr. Bell is in accord with local geologic opinion in his acceptance of the principal conclusions therein set forth.

The Lion Oil Refining Company's Hays A-9 well, located in the SW. ¼, NE. ¼, Sec. 4, T. 16 S., R. 15 W., Union County, Arkansas, was drilled to a depth of 7,225 feet. The test penetrated beds tentatively correlated with the Lower Marine formation of the Trinity group (Comanche series) and encountered rock salt at 5,960 feet. From this depth the drill remained in solid rock salt until the well was lost due to sticking of the drill stem. A thickness of 1,295 feet of salt was penetrated.

The announcement of the existence of rock salt underlying the Smackover field came as a distinct surprise to geologists familiar with coastal plain problems. Opinion was general that a comparatively thin stratum would be penetrated which would be interpreted as the northern edge of the assumed mother salt bed from which the salt of the interior domes was derived. But the great thickness actually penetrated with the total thickness undetermined cast considerable doubt on this hypothesis and encourages the view that the Smackover salt may be intrusive in origin. The vexing question of the age of this salt, and its related problem—the age of the salt of the salt domes of North Louisiana and East Texas—remains unanswered. The author's guess that the salt is referable to the Permian calls forth little opposition at present.

The paper contains two structure maps, a hypothetical cross section, and a tabulation of well data. The concise discussion of the mechanical procedure required in drilling the well makes the paper of special value to deep well drillers everywhere.

C. L. MOODY

SHREVEPORT, LOUISIANA
September, 1933

[1] W. C. Spooner, "Salt in Smackover Field, Union County, Arkansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 6 (June, 1932), pp. 601–8.

Geologie Südamerikas (Geology of South America). By H. GERTH. Part I, vii+198 pp., 17 tables, 38 figs. (Gebrüder Borntraeger, Berlin, 1933.) Cloth. Price, 22 RM.

The first volume of this detailed and specialized book which constitutes the fourth volume of *Geologie der Erde* (The Geology of the World, edited by Professor Krenkel, Leipzig, and published by Borntraeger, Berlin) has appeared. It contains 17 instructive plates, 36 figures in the text and 198 pages in all and will be heartily welcomed by geologists in general, but especially by exploring geologists and prospectors who, like the reviewer, have until now tried in vain to acquaint themselves exactly with the salient features of the general geology of South America. At the beginning of 1927, when the reviewer was a field geologist and *petrolero* in Colombia, there was actually no book that he could use as a guide to the general geology of the continent and to which he could turn for certain information on geology outside the limits of the geology of Colombia proper.

Such an introduction has now been given by Gerth, with a summary of the present-day problems of South American geology. He gives the broad features of the geological development of the continent and for reasons easily understood refrains from regional details.

Volume I has to do with geological history up to the end of the Paleozoic period.

In South America the non-folded eastern part is faced by the folded Cordillera region, which bounds it on the north and west. The main divisions in the eastern part—Guayana, Brazilia, and Patagonia—are separated by the Amazon Basin and the Rio Negro depression; they are old cores the basements of which are only partly covered by more recent non-folded sedimentary deposits. From the Silurian age onward, the Amazon Basin was a site for the deposition of marine Paleozoic remains.

About the same time the great Paleozoic depression of the Gondwanides was formed. This was an old folded mountain range on the eastern and western boundaries of the Brazilian and African continent and had no connection whatever with the South American Andes. At the end of the Paleozoic period the great southern Brazilian mass developed in the basin which is to-day drained by the Paraná and in which early Mesozoic sediments and lavas accumulated. Later movements caused the southern part of Brazil to sink and thus make room for the deposition of the Pampas sediments of Argentina, which are dominated by the old cliffs of the Pampas Sierras.

The first part (to page 82) describes the pre-Paleozoic basement rocks. In discussing the old cores in the east (I), Gerth deals at first with Guayana and Brazilia (divided into Archean primitive rocks and Algonkian) and then with the basement rocks in Uruguay and Argentina (Uruguay proper and Sierra Pampas) and Patagonia. The author (II) then turns his attention to the primary rocks of the Cordilleras, where conditions are similar to those observed by the reviewer in Colombia and Venezuela. Outcrops of Archean rocks, many of which are huge, are found in the central part of the Central Cordillera and in the western slopes of the Eastern Cordillera of Colombia. The north coast of Venezuela near La Guaira originates from the components of old, probably in part Archean, rocks. Similar rocks crop out in the road leading from La Guaira to Caracas. Pre-Cambrian formations are to be found on the Central, Western, and Eastern Cordillera (eastern slopes as well

as in the Choco) and probably in the Eastern Cordillera of Colombia. Gerth further describes at the outset the conditions in the northern Cordilleras in Venezuela, Colombia, and Ecuador. He then discusses the Cordilleran area of Peru and the old rocks of the Chilean coast and the Patagonian Cordillera. At the end of the section Gerth gives a summary devoted to primary rocks in general and the Brazilides, a term applied by Keidel in 1922 to the mountainous region formed from old rocks extending to eastern Brazil in a north-northeasterly direction.

The second large section of the book (pages 83–199) deals with the older Paleozoic rocks (IV). In Colombia there are interesting and most complicated layers in the foothills of the eastern Cordilleras, in the Magdalena Valley (Curumani-Santa Rosa). Sections of the old Paleozoic formation form the bar of Peñon, which can be regarded as the most northerly continuation of the Colombian Central Cordillera, crossing Magdalena River near the little town of El Banco. About the time of the oil formation in the Magdalena Valley, that is, chiefly in the Oligocene period, this bar was a divide between the open Tertiary sea and *Magdalena oil bay*. Old Mesozoic formations were observed on the Peninsula of Goajira. They also occur near Cristalina on the eastern slopes of the Central Cordillera (graptolitic lower Silurian deposits, and Ordovician, mentioned by Gerth on page 87 and discovered in 1927 by pupils of the late Dr. v. Böckh of the D'Arcy Exploration Company). Such formations are also found on the Antióquia railway not far from Puerto Berrío and at several other places in the Colombian Cordilleras. Gerth divides his data on the old Paleozoic rocks into two sections, Cambrian and Silurian, the latter being subdivided into Ordovician and Gotlandian. He makes some interesting remarks on indications of Caledonian folding in South America. The deposits of the younger Paleozoic rocks to which the next section (V) is devoted are classified under three headings, namely, Devonian, Carboniferous, and Permian. The details about the Permian deal with the Permian formation of northern Brazil on the borders of the Paraná Basin, and with the same formation in Argentina, southeastern Bolivia, and the Falkland Islands. The author concludes with a summary of his views on the South American Permian formation in general.

The last section of the book (VI) is devoted to the Gondwanides, which were previously mentioned. The Sierras of the Province of Buenos Aires, the mountains of the Falkland Islands, and the Argentinian Cordilleras are dealt with in the order mentioned. The author then gives some views on further traces of younger Paleozoic folding in the Cordilleras.

All those interested in geology will undoubtedly derive great satisfaction and considerable scientific benefit from the perusal of the first volume of *Die Geologie Südamerikas* and it is to be hoped that the second volume of this important work will soon be available.

KARL ERMISCH

BERLIN, GERMANY
August 18, 1933

"Petroleum, Erdöl-Lagerstätten und Schlammvulkane in Kolumbien, Südamerika" (Petroleum, Oil Deposits and Mud Volcanoes in Colombia, South America). By K. ERMISCH. *Die Naturwissenschaften* (Julius Springer, Berlin W. 9), Vol. 21, No. 30 (July, 1933), pp. 553–59; 2 tables; 3 figs.

The only commercial production in Colombia is located in the middle Magdalena valley and is derived from the Chuspas formation of Oligocene age, which is of brackish origin. Other parts of Colombia are probable oil territory. This is evidenced by an oil well completed in March, 1933, in the area of the Rio Catatumbo (probably Cretaceous oil), by many seepages in various parts of the country, and by mud volcanoes. The author enumerates ten groups of mud volcanoes, which he has visited and studied. The paper contains two tables on the stratigraphy of the country and three very good pictures of mud volcanoes.

EDWARD BLOESCH

TULSA, OKLAHOMA
September 6, 1933

RECENT PUBLICATIONS

CALIFORNIA

"The Vaqueros Formation, Lower Miocene of California, Volume I, Paleontology," by Wayne Loel and W. H. Corey. *Univ. California Bull. of Dept. Geol. Sci.*, Vol. 22, No. 3 (1932). 380 pp., 62 pls., 2 maps, correlation chart.

GENERAL

Minerals Yearbook 1932–33, by 49 authors on the staff of the U. S. Bureau of Mines. 61 economic and statistical surveys. Pt. I, "Review of the Mineral Industry"; Pt. II, "Metals"; Pt. III, "Nonmetals," including mineral fuels; Pt. IV, "Mine Safety." 819 pp., 90 illus. Supt. of Documents, Govt. Printing Office, Washington, D. C. Blue cloth. Price, $1.25.

"Petroleum and Natural-Gas Studies of the United States Bureau of Mines," by H. C. Fowler. *U. S. Bur. Mines Inform. Cir. 6737* (July, 1933). Includes chapters on technical problems: (1) "Petroleum Chemistry and Refining"; (2) "Production of Gas and Oil, Including Related Problems of Pipe-Line Transportation of Natural Gas"; (3) "Engineering Field Studies"; and (4) "Special Engineering Problems." 50 mimeog. pp.

"Vorbedingungen für den Tiefbau auf Erdöl" (Basic Conditions for the Deep Mining of Petroleum), by W. Schulz. *Inter. Zeits. für Bohrtech., Erdölbergbau und Geologie* (Vienna), Vol. 41, No. 15 (August, 1933), pp. 167–70.

The Mineral Industry During 1932, edited by G. A. Roush, Vol. 41 (1933). More than 30 authoritative contributors to as many chapters. "Petroleum and Petroleum Products," by Arthur Knapp. McGraw-Hill Book Company, New York. 930 pp. 6 x 9. Price, $12.00.

"Zur Entstehung und Migration des Erdöls" (Origin and Migration of Petroleum), by Karl Krejci. *Intern. Zeits. Bohrtech., Erdölberg. und Geol.* (Vienna), Vol. 41, No. 17 (September 1, 1933), pp. 191–95 (1st part).

"Present Distribution and Thickness of Mesozoic Systems," by Walter A. Ver Wiebe. *Bull. Geol. Soc. Amer.*, Vol. 44, No. 4 (August 31, 1933), pp. 827–63; 4 figs.

GEOPHYSICS

Aufsuchung von Wasser mit geophysikalischen Methoden (Research for Ground Water by Geophysical Methods), by J. Koenigsberger. Special

reprint, with English abstract, from *Beiträge zur angew. Geophysik*, Vol. 3 (1933), pp. 463–525. Akad. Verlagsgesellschaft m. b. H., Leipzig, Germany. 63 pp., 22 figs. $5\frac{3}{4} \times 8\frac{3}{4}$ inches. Paper. Price, M. 3.80.

INDIA

"Verschillende Typen van Tertiare Geosynclinalen in den Indischen Archipel" (Various Types of Tertiary Geosynclines in the Indian Archipelago), by J. H. F. Umbgrove. *Leidsche Geol. Mededeelingen*, Deel 6, Aflevering 1 (Leiden, Netherlands, 1933), pp. 33–43. In Dutch.

NEW MEXICO

"Geology and Ground-Water Resources of the Roswell Artesian Basin, New Mexico," by A. G. Fiedler and S. Spencer Nye. *U. S. Geol. Survey Water-Supply Paper 639* (1933). Supt. of Documents, Govt. Printing Office, Washington, D. C. Price, $1.00.

POLAND

"Considérations sur l'origine des huiles de Boryslaw et de Strzelbice" (Notes on the Origin of Petroleum in Boryslaw and Strzelbice), by H. Arctowski and I. Gottlieb. *Inst. Geophys. Univ. Lwow Communication 72* (Lwow, Poland, 1933), pp. 186–217, figs. 1–10. In Polish and French. These authors and others have several other reports on the physical characteristics of oil in different Polish fields.

ROUMANIA

"Zur Bildung der rumänischen Erdöllagerstätten" (On the Formation of Roumanian Petroleum Deposits), by Karl Krejci. *Kali, Verwandte Salze und Erdöl* (Halle, Germany), Vol. 27, No. 15 (August, 1933), pp. 185–87 (1st chapter).

CORRECTION

The U. S. Geological Survey maps, *Oil and Gas Fields of California*, and *Geological Map of the United States*, are obtainable at $0.50 and $2.50, respectively, from the Survey, Washington, D. C., not from the Superintendent of Documents as stated on page 1153 of the September *Bulletin*.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17 NO. 10 (OCTOBER, 1933), PP. 1287-1292

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

The World Petroleum Congress, organized by the Institution of Petroleum Technologists (London), and held in London, July 19–25, had more than 235 scientific papers on its program. J. BRIAN EBY, consulting geologist and geophysicist of Houston, Texas, described the meeting in *The Oil Weekly* (Houston) of August 7. The proceedings, papers, and discussions will be published in one volume, to be available through the secretary of the Institution of Petroleum Technologists, Aldine House, Bedford Street, London, W. C. 2, England. The following papers were listed in the geology and production sections of the provisional program.

Modern Developments in Geological Exploration

"Recent Oil Exploration by Electrical Methods," by Conrad Schlumberger

"The Limitations of Geophysical Methods and the New Possibilities Opened Up by an Electro-Chemical Method for Determining Geological Formations at Great Depths," by Oscar Weiss

"The Seismic Method," by J. H. Jones

"The Seismic Method," by F. Goldstone

"Regional Magnetic Study of the Pechelbronn Petroliferous Basin," by C. L. Alexanian

"The Application of Ultra-Violet Rays in the Investigation of Boring and Oil Tests," by A. Bentz and E. Strobel

"The Vertical Magnetometer," by James C. Templeton

"Structural Investigation by Electro-Magnetic Methods," by Karl Sundberg and H. Hedstrom

"The Economic Application of the Torsion Balance in Oil Prospecting," by James C. Templeton

"Co-operation between Geologists and Geophysicists," by R. Schreiter

"The Use of Geophysics in the Determination of Structure in the Argentine," by F. Fossa-Mancini

"Magnetic Anomalies in Oil Fields" (Healdton, Oklahoma), by A. Van Weelden

"The Regional Tectonical Features of the Wichita-Arbuckle Mountain Region in the Light of Geophysical Observations," by A. Van Weelden

"Mapping of Geological Structures by the Reflection of Elastic Waves," by F. Goldstone

"Remarks on the Use of Aerial Photographs for Geological Purposes," by Stanislaw Zuber

"Topographical Aspects of Aeroplane Surveying," by J. S. A. Salt

"On Some Kinds of Outcrops of Oil-Bearing Strata and Their Prospecting," by Stanislaw Zuber

"The Evaluation of Surface Evidences of Petroleum," by Gerald de P. Cotter

"The Construction of Maps of Subsoil Structure for the Purpose of Petroleum Geology," by D. Chahnazaroff

"The Scientific Foundations of Micro-Paleontology," by M. F. Glaessner

"The Application of Micro-Paleontology to Petroleum Geology," by W. L. F. Nuttall

"Micro-Petrology," by P. Evans

"The Aneroid Barometer in Reconnaissance Work," by T. Sutton Bowman

Geological Significance of the Regional Distribution of Oil Fields

"Geological Significance of the Regional Distribution of Oil Fields," by A. Wade

"The Distribution of Probable Source Rocks in Relation to Natural Gas and Petroleum Production in Alberta, Canada," by G. S. Hume

"The Oil Prospects of Western Canada," by Campbell M. Hunter

Geological Aspects of Oil-Field Development

"Contribution to the Study of the Phenomena which Accompany Accumulations of Gas in the Exploitation of Petroleum Deposits," by D. Chahnazaroff

"Gas Saturation Pressure of Reservoir Crude as a Factor in Efficient Operation of Oil Fields," by D. Comins

"Unit Development of Oil Fields," by J. B. Umpleby

"Well Spacing," by F. E. Wood

"Note on Accuracy Attained by Electrical Correlation in Drilling Wells," by T. Sutton Bowman

"Recent Developments in Electrical Coring," by Conrad Schlumberger

"Rejuvenation of Oil Fields by Natural and Artificial Water Flooding," by K. B. Nowels

Drilling

"General Principles Involved in Oil Well Drilling," by John A. Zublin

"Gravity and the Driller," by H. C. B. Hickling

"Mud Control of Formation Pressures, Heaving Shale, et cetera," by A. Frank Dabell

"Pressure Drilling," by B. J. Ellis and James Cuthill

"Measurement of the Deviation (Inclination and Azimuth) of Drill Holes by Means of the Electro-Magnetic Teleclinometer," by Conrad Schlumberger

Production

"Relationship between Rate of Production, Gas-Oil Ratio, and Ultimate Recovery," by I. I. Gardescu

"Modern Developments in the Raising of Oil," by A. E. Walling

HOYT RODNEY GALE is at 1775 Hill Drive, Eagle Rock, Los Angeles, California.

SIDNEY H. JOHNSON spoke before the luncheon meeting of the Houston Geological Society, August 10, on the "Greta Area."

ROBERT H. LYNN has been appointed vice-president in charge of land and geological departments of the Phillips Petroleum Company at Bartlesville.

LOREN PARKER, geologist, is now employed in the scouting department of the Continental Oil Company, Ponca City, Oklahoma.

LON D. CARTWRIGHT, Jr., of Beaumont, is associated with Fisher and Lowrie, consulting geologists, and may be addressed at their Houston, Texas, office at 713 Esperson Building.

FRANK R. VAN HORN, professor of geology and mineralogy in the Case School of Applied Science, Cleveland, died on August 1, at the age of 61 years.

ARNALDO BELLUIGI, of Parma, Italy, presented two papers before the World Petroleum Congress at London last July: one on geophysical contributions of the A. G. I. P. (Italian State Railways) in oil research in Italy and one on progress in petroleum research by electrical methods. The latter is published in Italian in *L'Industria Mineraria*, Vol. 7, No. 6 (1933).

HOYT S. GALE, formerly geologist for the Gulf Oil Corporation in California, has been commissioned by the United States Geological Survey to make a detailed study and report on the geology of the Hawaiian Islands.

C. H. DRESBACH, formerly with the Sinclair Exploration Company in Venezuela, has received the degree of Master of Science from the University of Pittsburgh, and is now with the Gulf Research and Development Corporation, 327 Craft Avenue, Pittsburgh, Pennsylvania.

FRANCES CHARLTON, formerly of the department of paleontology, University of California, Berkeley, is now employed by the Pure Oil Company, Houston, Texas.

L. G. WEEKS has changed his address from Sao Paulo, Brazil, to General Ballivian, FCCNA, Salta, Argentina, S. A.

SAM ZIMMERMAN, geologist for the Humble Oil and Refining Company, has been transferred from Houston, Texas, to Guthrie, Oklahoma.

STANLEY E. JAY has changed his address from 731 West Ferguson Street, Tyler, to 307 North Adams Street, San Angelo, Texas.

GEORGE SHEPPARD, formerly of 3 Village Road, Garden Village, Hull, England, may now be addressed at Casilla 410, Guayaquil, Ecuador, S. A.

W. T. THOM, JR., and R. M. FIELD, of Princeton University, have a communication "Geologic Research Work Near Red Lodge, Montana," in *Science* of August 4.

The committee on grants-in-aid of the National Research Council, Washington, D. C., made 74 grants early in 1933 for individual research, from 249 applications. Fourteen of the grants went to geological research. The following are of interest to petroleum geologists: CHARLES I. ALEXANDER, Texas Christian University, "Fossil Ostracoda of Texas"; MARGARET FULLER BOOS, Madison, Wisconsin, "Granites of the Front Range, Colorado"; ARTHUR KEITH, United States Geological Survey, "Mountain Building in New England and Quebec as Evidenced by Ordovician and Silurian Formations"; EVANS B. MAYO, Cornell University, "Sierra Nevada Granites Between Mono Lake and Round Valley, California"; ELIZABETH MCCOY, University of Wisconsin, "Rôle of Micro-Organisms in the Diagenesis of the Sediments of a Fresh-Water Lake"; RAYMOND C. MOORE, University of Kansas, "Stratigraphic and Paleontologic Studies of the Carboniferous Rocks of Wyoming"; FRANCIS L. PARKER, Cushman Laboratory for Foraminiferal Research, "The Genus *Bulimina* and Related Genera"; WILLIAM F. PROUTY, University of North Carolina, "The Silurian System in the Southern Appalachian Mountains."

W. H. HAAS, professor of geology and geography of Northwestern University, Evanston, Illinois, has announced that anonymous donors have provided the following funds in honor of the late U. S. GRANT, formerly head of the department of geology and geography: $300 to pay for the first season of a new series of lectures on geology and geography; and $150 for a graduate scholarship in the same subjects.

HOWARD E. SIMPSON is the new head of the department of geology and geography in the University of North Dakota and director of the North Dakota State Geological Survey.

The San Antonio Section of the Association will hold its annual technical meeting in Corpus Christi on Saturday, October 28, 1933. The general program will be devoted chiefly to problems of Southwest Texas. Papers scheduled for presentation include: "The Structure and Sand Conditions of Tomball, Conroe, and Pettus"; "The Structure and Sand Conditions of Pettus and the Oil Fields of the Laredo District"; "Detailed Sections and Structural Features of the Lissie and Beaumont Formations."

The technical meetings will be preceded on Friday, October 27, by a field trip to study surface exposures of the Lissie and Beaumont formations in Victoria and Refugio counties. On Sunday, October 29, following the technical meetings, there will be a second field trip to Live Oak, Bee, and Goliad counties to study the Goliad and Lagarto formations.

T. J. GALBRAITH, The California Company, San Antonio, Texas, is in charge of the program.

RICHARD V. HUGHES received the degree of Ph.D. in geology at The Johns Hopkins University last June and went temporarily with the United States Forest Service on the Cumberland Purchase Unit, Kentucky. His home address is 1417 Sixteenth Street, Auburn, Nebraska.

PERRY R. LOVE is employed by the Geophysical Research Corporation at Tulsa, Oklahoma.

CHARLES GILL MORGAN, formerly professor of geology at Southern Methodist University, Dallas, and seismologist for the Geophysical Research Corporation, Tulsa, sailed on October 1 with the second Byrd Antarctic Expedition as geologist and geophysicist. His investigations in the South Polar regions will include the determination of the various thicknesses of the ice cap by the seismic method and the geological study of the exposed land masses of that part of the continent claimed for the United States by Admiral Byrd on his previous trip. Until the return of the expedition in May, 1935, Morgan will receive all mail by radio by addressing the Byrd Antarctic Expedition II, United States Navy Yard, Boston, Massachusetts.

J. M. ARMSTRONG, geologist for the Sinclair Prairie Oil Company, has been transferred from Eastland to Fort Worth, Texas.

H. E. ROTHROCK has joined the staff of the University of Tulsa's Downtown College as instructor of petroleum geology. Rothrock, who was formerly chief geologist of the Superior Oil Corporation, will continue his consulting practice in Tulsa in addition to his work with the University.

E. G. ALLEN has changed his address from the Shell Petroleum Corporation, Houston, Texas, to 135 El Morado Court, Ontario, California.

WILLIAM HENRY COREY is temporarily in Tucson, Arizona, for his health after two years on the Isthmus of Tehuantepec for the Standard Oil Company of California. His permanent address is 810 Gaviota, Long Beach, California.

PHILIP ANDREWS, formerly with the Standard Oil Company of California in South America, has accepted a position as geologist with the Gulf Oil Company in eastern Venezuela. His mail address is the Venezuela Gulf Petroleum Company, Cuidad Bolivar, Venezuela, S. A.

N. W. BASS, United States Geological Survey, has moved from Wichita, Kansas, to Washington, D. C.

MINETTE RIES, Phillips Petroleum Company, and formerly secretary-treasurer of the West Texas Geological Society, has been transferred from San Angelo to Amarillo, Texas.

GLENN G. BARTLE has been appointed professor of geology and head of the division of physical sciences in the newly organized University of Kansas City, at Kansas City, Missouri.

WALTER J. BOYLE, formerly of Wichita, Kansas, has been made district geologist for the Phillips Petroleum Company, at San Antonio, Texas. His address is 1721 West Mistletoe.

DWIGHT J. EDSON, of the Edison Petroleum Company, has moved from San Angelo, to 1507 Esperson Building, Houston, Texas.

WILLIAM T. FORAN, formerly of St. Maries, Idaho, has accepted a position with the Standard Oil Company of South America and may be addressed General Ballivian F. C. C. N. A., Argentina, S. A.

E. W. K. ANDRAU, geologist for the Shell Petroleum Corporation, who has been at The Hague, Holland, for the past several months has returned to Houston, Texas.

ROBERT M. FRANKS has changed his address from 904 Milam Building, San Antonio, to the Second National Bank Building, Houston, Texas.

CHARLES R. HOYLE, geological engineer for the Phillips Petroleum Company, has moved from 201 West Franklin Street, Shawnee, Oklahoma, to 3004 N. W. Nineteenth Street, Oklahoma City, Oklahoma.

W. L. MOREMAN, formerly assistant in paleontology at Texas Christian University, Fort Worth, Texas, is now stationed at Oklahoma City, Oklahoma, as paleontologist for the Magnolia Petroleum Company.

President FRANK R. CLARK, chief geologist of the Mid-Kansas Oil and Gas Company, Tulsa, Oklahoma, was on an extended trip in Texas in the month of October. Besides visiting other local groups, he attended the Association research committee meeting on October 5, and the American Institute of Mining and Metallurgical Engineers Petroleum Division meeting on October 6 and 7, both at Dallas, Texas.

J. H. JENKINS, general manager of the producing division of the Associated Oil Company, Los Angeles, has been elected a vice-president of the company.

At the regular monthly meeting of the San Antonio Geological Society, on the night of September 11, there was a discussion of the correlations of typical well logs of the Laredo area by DON DANVERS and HARVEY WHITAKER. The meeting was attended by about 60 southwest Texas geologists.

J. C. POLLARD is in charge of the Magnolia Petroleum Company's torsion-balance operations. Pollard was formerly with the Humble Oil and Refining Company and the Coastal Oil Finding Company at Houston. His headquarters will be at Houston, Texas.

C. I. ALEXANDER, formerly associate instructor in paleontology at Texas Christian University, Fort Worth, Texas, has been employed as a paleontologist by the Magnolia Petroleum Company and will be stationed at Shreveport, Louisiana.

ARTHUR KEITH, author of several United States Geological Survey folios on the Tennessee Valley area, has been studying dam-site problems at Cove Creek at the direction of President Roosevelt and Arthur Morgan, chairman of the Tennessee Valley Authority.

R. B. HARRINGTON, of the Dokenva Gas Corporation, has headquarters at Richmond, Kentucky.

B. B. WEATHERBY, president of the Geophysical Research Corporation (an Amerada company) has announced that the manufacturing division of the corporation has been moved from New Jersey to Tulsa, Oklahoma, where the executive and operating headquarters are located.

C. and M. SCHLUMBERGER presented a paper entitled, "Electrical Coring: Its Application in Rumania in 1931–32" (Preprint No. 9), and with H. G. DOLL a paper, "The Electricmagnetic Teleclinometer and Dipmeter," before the World Petroleum Congress at London last July.

C. E. DOBBIN, of the United States Geological Survey at Denver, Colorado, was in southwestern Utah in October.

HARVE LOOMIS gave a talk on the Dutch East Indies before the San Antonio Section of the Association, October 2.

SHEPARD W. LOWMAN spoke on the subject, "Oklahoma Mountains, a Re-study," before the Tulsa Geological Society, October 2.

L. C. SNIDER, editor of the Association *Bulletin*, was in the Mid-Continent and Gulf Coast regions in September and October for Henry L. Doherty and Company, New York.

J. WILKINSON HOOVER, formerly with The California Company, at San Antonio, Texas, is now with The Bahrein Petroleum Company at Bahrein Island, Persian Gulf.